HUNGER SIGNS IN CROPS

A SYMPOSIUM

Prepared by

FIRMAN E. BEAR
B. E. BROWN
A. F. CAMP
H. D. CHAPMAN
H. P. COOPER
O. WESLEY DAVIDSON
LEROY DONALD
G. N. HOFFER
G. V. C. HOUGHLAND
H. A. JONES
WESLEY P. JUDKINS
B. A. KRANTZ
J. E. McMURTREY, Jr.
WERNER L. NELSON
E. R. PARKER
E. R. PURVIS
GEORGE D. SCARSETH
J. J. SKINNER
NORMAN J. VOLK

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Foreword to the Second Edition

WHEN HUNGER SIGNS IN CROPS was first projected, those who cooperated in preparing the book believed they would be offering the agricultural public a much-needed treatise on the subject. Although rapid advances had been made by agricultural scientists in the study of nutrient-deficiency symptoms in crops, their work had not been assembled in convenient form.

As in all such ventures, there was much uncertainty about the reception such a book would be accorded. Concern on this point was soon dispelled. Immediately after its announcement, orders began pouring in. Three printings were required, and high praise for the volume came from numerous organizations and individuals. The book was widely used by college professors, research and extension specialists, industrial chemists and agronomists, county agents, and teachers of vocational agriculture. Many farmers found it of much use in deciding on their fertilizer program.

Rapid advances have been made in our knowledge of this subject, so that it has become necessary to prepare an entirely new edition. This second edition includes much material that has not previously been published. Many hours of unselfish labor have been devoted by the chapter authors to the revision. Credit is due also to their associates and colleagues who have offered suggestions and furnished photographs.

Accordingly, the American Society of Agronomy and the National Fertilizer Association are now pleased to present to the public this second edition of HUNGER SIGNS IN CROPS. We hope it will continue to serve the cause of an ever better American agriculture.

FIRMAN E. BEAR, *President*
American Society of Agronomy

RUSSELL COLEMAN, *President*
The National Fertilizer Association

Washington, D. C.
September 1949

Foreword to the First Edition

WHEN we human beings lack certain essential nutritive elements, we get serious nutritional diseases — rickets from a lack of calcium, phosphorus, and vitamin D; nutritional anemia from a lack of iron; beriberi from a lack of thiamin; pellagra from a lack, probably, of nicotinic acid; scurvy from a lack of ascorbic acid; and so on through a considerable list. The symptoms of these diseases are pretty clearly recognized by physicians.

Even when there is no acute disease, an essential nutritive element may be sufficiently lacking to give us a borderline case—some minor but perhaps troublesome ailment that keeps us from being really healthy. Frequently these borderline ailments too can be diagnosed by the shrewd eye of the physician, sometimes supplemented by laboratory tests.

Much of this knowledge is new, and it is of untold value. It means that many human ills—even many untimely deaths—can now be considered absolutely needless; much of our common inability to meet the demands of life with full nervous and physical vigor can be eliminated.

Best of all, we do not have to depend on the physician to achieve these things for us. As the modern knowledge of nutrition spreads, anyone who will take the trouble to understand and use it has the control of life and health, insofar as they are affected by food, within his own hands.

At the same time, farmers are now better able to feed their livestock for maximum health and productiveness because knowledge of human and animal nutrition have advanced together.

What has all this to do with the subject of fertilizers and crop plants?

There is a close connection in more ways than one. Plants too are living things. They take in food and convert it into body tissues and energy; they can be healthy and vigorous or they can be ill and die; they have their acute diseases and their minor ailments; and they require certain nutritive elements just as surely as do we human beings. Many of these elements, in fact, are the same ones we require. Without them, the plant too suffers from hidden hunger. It needs a balanced diet as much as we do.

You cannot tell a plant to stick out its tongue and say "Ah," but there are other ways of examining it for symptoms of ill health. It may show unmistakable signs of hidden hunger—nutritional deficiency—if we can only recognize them.

The purpose of this book is to help us to recognize the signs of nutritional deficiency in crop plants. It was written by scientists who have made a close study of this subject, each in his own particular field, for many years.

As in the case of human nutrition, the best thing about this knowledge is that it is not all in the hands of the experts; it can be used by the layman. The farmer who will take the trouble to study the symptoms of malnutrition in plants is in a position, in many cases, to correct the difficulties himself.

Much of this knowledge also is new. A few years ago, for instance, what farmers called "firing" of corn was attributed to drought. Now it is known that though firing of corn is made worse by lack of moisture, it is fundamentally due to nutritional deficiencies—shortage of essential elements in the food supply of the plant.

And just as one nutritional element after another was found to be vitally necessary for human health, so one element after another was found to be essential for the health of plants. There is a real parallel between the discoveries in these two fields.

After it was found that lack of one or another plant food could cause definite nutritional diseases in plants, the next step was to make a close study of the symptoms. A number of scientists have been doing this in the United States and other parts of the world for many different kinds of plants and many plant foods. They have used field studies, plot studies, pot studies, and nutrient-solution studies.

The work requires great patience and a close knowledge of what the plant is like in normal health. The scientist notes down every visible effect or symptom in a plant deprived of this or that element, being careful not to be fooled by something that is not a symptom. Then he tries to put the complicated lot of symptoms into some order and describe them with the utmost accuracy so they will be understandable and useful in diagnosis.

That is what has been done in this book for a considerable number of important crops.

Some of the chapters include a key for quickly identifying a deficiency by its symptoms. These keys are arranged in the form

sometimes used for plant identification, with all coordinate headings marked by the same letter, rather than in ordinary outline form. There is also a wealth of illustrations in color and in black and white. With the accompanying legends, they are intended to tell as complete a story as possible by themselves.

The book is not to be considered as the final word by any means. Active work is still going on in this field, and much remains to be done. The reader will note, for instance, that there is not as complete or as definite information about all deficiencies in some crops as in others—sometimes because of inherent difficulties, sometimes because less research work has been done in the latter cases.

Thus, the farmer will need to use caution in diagnosing deficiency symptoms, and where there are uncertainties he will want to get expert help from scientific workers. He should be especially careful about confusing deficiency symptoms with conditions due to disease, organisms, insects, or other causes.

In a few cases, injuries caused by excesses of certain elements are mentioned in the text or illustrated in figures, but no attempt has been made to cover this subject systematically.

Now a brief account of how the book came to be written.

Early in 1936, The American Society of Agronomy felt that enough is known about the symptoms of malnutrition in plants—though there is much yet to be discovered—to prepare a monograph on the subject, and that such a monograph would fill a growing need. The Committee on Fertilizers, headed by R. M. Salter, appointed a subcommittee to look into the possibilities, with J. E. McMurtrey, Jr., as chairman. As a first step, this group got the assistance of the Plantfood Research Committee of The National Fertilizer Association in rounding up all available colored photographs of malnutrition symptoms, and these were exhibited at the 1936 meeting of the Society of Agronomy.

Early in 1937, plans were outlined for the book, HUNGER SIGNS IN CROPS, and the authors were selected. A major problem from a practical standpoint was to keep the price from being prohibitive; it would be very high for a small edition of a book with as many colored illustrations as were needed in this case to give maximum usefulness. However, the authors, as members of The American Society of Agronomy, contributed their work without compensation; Charles J. Brand and H. R. Smalley contributed much time and effort that would ordinarily have been part of overhead expenses; and The National Fertilizer Association, through its Soil

Improvement Committee, agreed to be responsible for the sale of enough copies, in addition to the ordinary demand, to make a fairly large printing possible and thus materially reduce the cost per copy. (While these acknowledgments are being made, credit should also be given to Marion J. Drown for a great deal of detailed editorial work on the chapters, and to Mary A. Bradley for indexing.)

So wide a range of material on malnutrition symptoms in plants has not before been brought together in a single volume, and it should be useful alike to farmers, students and teachers of agriculture, technical workers, and everyone concerned with the proper management of soils and crops. Care has been taken to keep the book as nontechnical as possible so as to give it wider usefulness. Even the usual lengthy bibliographies have been cut down to a few references. Fertilizer analyses, however, appear throughout the book in the technical form. This is so familiar to farmers and others concerned with agriculture that it hardly needs explanation. In such an analysis (4-10-6, for example) the first figure stands for the percentage of nitrogen (N) in the total mixture, the second for the percentage of available phosphoric acid (P_2O_5), and the third for the percentage of available potash (K_2O).

The editor would be remiss if he did not emphasize one other reason why he thinks the book is important aside from the main point, which, of course, is its immediate practical value. It marks one more step in the study of nutrition from the soil on up through man. What the soil does not have, plants will not get, and animals and men will lack also. The welfare of man is intimately bound up with the welfare of soils and plants because all our food comes in the first instance from plants; even our meat, milk, eggs, and fish are simply plant substances rebuilt into other forms.

There is a vastly significant story here which we can see as yet only in dim outline. Much more will be heard about it as times goes on, and everything that will help to fill in the many gaps in the story is a contribution to human welfare.

Gove Hambidge
(Editor, First Edition)

Washington, D. C.
March 1941.

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CHAPTER I

Why Do Plants Starve?

By George D. Scarseth and Norman J. Volk [1]

NO ONE worries about a healthy plant. It is when a plant fails to grow vigorously that the farmer becomes concerned. A plant will slow down in its normal rate of development or will show other signs of trouble whenever any one of the many factors that contribute to its well-being gets out of balance. The Indian learned that burying a fish under a corn hill produced better plants, and that corn grew better where a brush pile had been burned. The Indian did not realize that he fertilized the soil with nitrogen and phosphate from the fish and with potash from the wood ashes. Other necessary elements also were provided by the fish and the ashes. What they were did not matter so long as there was enough fish and ashes and not much corn was needed.

THE PLANT NUTRIENTS

Since corn is a widely known plant, let us use it to obtain a picture of the materials that such a plant requires for its growth. It will be helpful, as background for a better understanding of the articles in this book, to have a clear conception of the kinds and amounts of materials required to produce 100 bushels of corn.

The plants producing 100 bushels of corn on 1 acre of land would consist of about:

4,000 pounds of stover
1,400 pounds of cobs
5,600 pounds of shelled corn
5,200 pounds of roots and stubble

—a total of about 16,200 pounds of air-dry matter. Excluding all water, this amounts to about 14,200 pounds of moisture-free dry matter. In table 1 are listed the raw materials needed to produce this amount of dry material.

It is evident from this table that plants require the vital nutrients in widely differing amounts. Each substance also has its own peculiarities. Some, for example, may be present in the soil in plentiful quantities yet be unavailable to plants because they are

[1] George D. Scarseth is director of research, American Farm Research Association, and Norman J. Volk is associate director, Purdue University Agricultural Experiment Station.

TABLE 1.—KINDS AND APPROXIMATE AMOUNTS OF RAW MATERIALS USED PER ACRE BY CORN PLANTS PRODUCING AT THE RATE OF 100 BUSHELS TO THE ACRE

Substance[2]	*Chemical Symbol*	*Pounds per acre*	*Approximate equivalent*
Water	H_2O	4,300,000 to 5,500,000	19 to 24 inches of rain
Oxygen	O_2	6,800	Air is 20 percent oxygen
Carbon	C	5,200 carbon or 19,000 carbon dioxide	Amount of carbon contained in 4 tons of coal
Nitrogen	N	130	4 100-pound bags of a 32 percent nitrogen fertilizer
Phosphorus	P	22	2½ 100-pound bags of 20 percent superphosphate
Potassium	K	110	2 100-pound bags of 60 percent muriate of potash
Sulfur	S	22	22 pounds of yellow sulfur
Magnesium	Mg	33	330 pounds of Epsom salt
Calcium	Ca	37	93 pounds of limestone
Iron	Fe	2	2 pounds of nails
Manganese	Mn	0.3	1 pound of potassium permanganate
Boron	B	0.06	¼-pound box of common borax
Chlorine	Cl	Trace	Enough in the rainfall
Iodine	I	Trace	1-ounce bottle of tincture of iodine
Zinc	Zn	Trace	The shell of one dry-cell battery
Copper	Cu	Trace	25 feet of No. 9 copper wire

tied up in chemical compounds the plants cannot use. In order to have a better understanding of what these nutrients do for plants and why plants may starve for lack of them, let us review a few facts about each.

WATER

From the roots that reach into the soil to the tip of the most remote leaf, a plant is one continuous water pipe. The solid structures of plants are made up of cells that consist of delicately organized gel-like substances (colloids) that have a great attraction for water. This attraction pulls water into the plant with such a strong force that almost 99 percent of certain parts of the cells may be water—water that has been extracted from soil containing perhaps only 15 or 20 percent.

The water system in the plant is the medium through which the nutrients pass—whether upward through the roots or downward through the leaves—to the proper plant compartments to be built

[2] The analyses for nitrogen, potassium, phosphorus, magnesium and calcium were made on corn at Lafayette, Ind., in 1938, 1939 and 1940. The other figures are from various sources. The composition of corn plants would vary on soils of different levels of fertility, and that of other types of crops would vary from that of corn in minor details.

into such foods as sugars and amino acids (the building materials of protein), which in turn are transformed into cellulose and other compounds that make up the solid structures of the plant. Any by-products or excess material can be carried out of the plant by the water to be excreted back into the soil or into the air. In fact, roots give off carbon dioxide, which with water forms a weak acid that aids in dissolving minerals in the soil.

The normal functioning of a plant cell depends on an adequate intake of water so that turgor (normal tension or rigidity) can be maintained and the tissue-building process can proceed. Since water is continually passing out of a plant—as water vapor—through the stomata, or breathing pores of the leaves, turgor depends on maintaining a delicate balance between intake of water through the roots and outgo through the leaves. The cell sap contains various salts that exercise a "pull" on water, so that it will pass from a zone of low salt concentration in the soil to one of high salt concentration inside the plant cells—a process called osmosis. An excessively high salt concentration in the soil near the roots, resulting from too localized an application of fertilizer, may upset this process and cause the plant to lose water to the soil instead of absorbing it. The turgor of the cells then decreases and the plant wilts.

Any slight decrease in turgor upsets the machinery inside the leaf, and some symptoms that resemble malnutrition may show up. Thus the appearance of the plant may suggest starvation of nitrogen, potassium or some other element. In fact, there may actually be starvation, for droughts that cause plants to suffer for water may also affect the availability of nutrients and their accessibility to the roots. Roots are dependent on the movement of plant nutrients in the soil moisture. The movement of nutrients in the soil decreases as the soil moisture becomes depleted.

Oxygen

Fortunately the earth is blessed with a liberal supply of oxygen, which is as vital to plants as it is to man. It is seldom realized that approximately 50 percent of the composition of the dry matter in a plant is oxygen. It combines with the other elements listed in table 1, forming oxides and complex organic compounds. When a plant is functioning in full vigor and health there is a shifting and balancing of the oxygen between the elements that are being rearranged into plant-tissue parts. This shifting of the oxygen is

called oxidation when it involves adding oxygen and reduction when it involves taking away of oxygen.

In certain reduced forms, some elements become poisonous to the plant. Two such poisons that are very common are the nitrites and sulfites. In the oxidized forms—that is, with oxygen added—these become nitrates and sulfates, which are nontoxic. Reduction is as necessary as oxidation in healthy plants, however, because some compounds such as the nitrites are reduced still further to be used in building proteins.

Any upset in the balance of oxidation and reduction processes resulting from an unbalance in the nutrients taken into the plant will show up in an unhealthy symptom. Potassium may be mentioned as an important element affecting the oxidizing and reducing processes. When insufficient potassium is present in a plant such as corn, iron is made insoluble by excessive oxidation and accumulates in the nodes.

Carbon

Carbon appears in many forms—as the pure crystalline diamond, as graphite in "lead" pencils and axle grease, as coal and soot, as the carbon dioxide that gives the sparkle and fizz to soda water. In plants, it is a brick in the cell walls of the tissue, a component of sugar, an atom in the flavor of the juices, a part of the structure of color, and even an element in the fragrance of the blossom. In fact, carbon is the keystone of all organic substances. Before there could be life, carbon had to be organized into many of its thousands of combinations with other elements.

Carbon is pulled out of the carbon dioxide of the atmosphere and built into these extraordinary structures by the energy of the sun acting on the green sacks of chlorophyll in the cells of the leaves. This is a master construction job not yet duplicated by man. Whenever a plant is unable to perform this construction job with carbon because of a shortage of some element necessary to the process—or because of an excess, from which an unbalance sometimes results—some symptom of abnormal functioning may appear.

It is seldom appreciated that plants must use carbon for their growth in the large amounts indicated in table 1. The air contains only about 3 one-hundredths of 1 percent of carbon dioxide. Thus vast volumes of air must be worked over by plants in order to obtain enough carbon in the form of carbon dioxide. In fact, if the air were richer in this substance, plants could grow faster and bigger

than they now do. The plants of the coal age did grow bigger than modern plants, and some geologists have held the theory that the atmosphere was richer in carbon dioxide then than now.

Nitrogen

Modern farming practices are generally nitrogen-depleting. When America passed from the Indian to the white man, the storehouse of nitrogen in the organic matter of the forest and prairie soils was opened for rapid emptying. In the warm climate of the South the emptying did not take long; in the cooler North it has been a slower process. Crop production today depends largely either on restoring organic matter to the soil in order that, through decay, it may furnish a revolving supply of nitrogen for crops, or on supplying nitrogen in the form of fertilizers. Both procedures are necessary for practical reasons.

There are about 75 million pounds of nitrogen in the air above every acre of land and sea, but to most plants it is as useless in this gaseous form as sea water is to a thirsty man. The atmospheric nitrogen must be combined with oxygen, carbon or hydrogen before it is of any use to growing plants. Some bacteria, such as those on legume roots, are able to perform this miracle. The chemist too can "fix" atmospheric nitrogen in fertilizer forms. Nature supplied nitrogen in forms available to plants in relatively small amounts in the organic matter of virgin soils. The process was a slow one.

Plant roots take up nitrogen in the form of ammonium and nitrate salts. Inside the cells these are converted into amino acids, of which there is a large number. The amino acids are recombined to form proteins. Any unbalance, whether from insufficiency or excess, in the supply of nutrients will upset this process. Since nitrogen, as the most important plant-food element in proteins, is used in such large quantities, a deficiency is very common in the case of plants grown on most upland soils.

Potassium

If you stood leaning against the wall of a bank that had a million dollars in its vaults, and you had only one dime in your pocket, there would be a total of one million dollars and ten cents within the area occupied by the bank and you. Out of this great sum, however, only the single dime in your pocket would be available for your use. A soil may have a total of 40,000 pounds of potash

(potassium oxide, K_2O) stored within a volume of 1 acre to a depth of 6 inches, but will usually have only 100 to 600 pounds, more or less, held in such a way that it is immediately available to plants.

No practical device is known that will quickly release the vast store of unavailable potassium in the soil for the use of plants. In view of the large amount needed, it is clear that the fertilization of soils by adding available potash to them is one operation plant growers must practice.

It seems strange that plants should need so much potassium when, so far as is now known, they do not build it into the structure of any of their parts. A plant will hold its potassium salts from being washed or leached out as long as it is living, but as soon as the plant is killed by cutting, the potassium, no longer held, will be washed out readily—as, for example, by rain on dried hay or corn shocks. Some potassium salts will also move from the plant back into the soil as the plant matures.

Not much is known about the function of potassium in plants. More is known about what happens to a plant when this element is deficient. From such information, theories are advanced that potassium enhances the plant's ability to resist disease, cold and other adverse conditions, and that it functions in the processes whereby sugars are made from carbon dioxide and water. Perhaps it acts as a condenser or "squeezer" in focusing the energy of the sun to a point where these two compounds will combine.

Potassium starvation is so common in most of the important crops that all growers should know its symptoms.

Phosphorus

The threads in plant cells that pull the materials of the cell's interior apart to form two new cells contain phosphorus. If the supply is scanty, the rate of cell division is slowed down and the plants remain stunted and spindling. The formation of sugar seems to be independent of the phosphorus supply, for a phosphorus-starved plant will continue to form sugar to such an extent that the amount actually becomes abnormally large. Some plants tend to turn reddish or purplish in color with the increase in sugar content, and this is one symptom of phosphorus starvation. The high sugar content may also be associated with a decrease in the formation of starch and cellulose from the sugar. The formation of cellulose is a part of cell-wall building and cell division; thus the theory

holds fairly well that the formation of new cells requires an adequate amount of phosphorus.

Phosphates, the forms in which the plants utilize phosphorus, are also a part of certain of the amino acids that form phosphate-bearing proteins.

Since most soils have a marked capacity to convert available forms of phosphorus into unavailable forms, the behavior of this element in relation to the reaction of the soil and to the clay and organic-matter content, is of tremendous economic importance. This subject is too lengthy to discuss here; the reader may refer to textbooks on soils for details.

Because of the loss of phosphorus through the destruction of organic matter by farming practices, through the removal of crops, and through the loss of soil by erosion, phosphorus is very generally deficient in soils. A study of phosphorus-deficiency symptoms in crop plants is likely to reveal to the farmer that the situation is more acute than he realized.

Sulfur

Sulfur is a major plant nutrient that has rarely been in the spotlight. Plants frequently contain more sulfur than phosphorus, calcium or magnesium, yet we seem to be better acquainted with the latter elements in their effect on crop production. Pass a cabbage field when it is thawing out after a killing frost, and the smell of hydrogen sulfide coming from the decomposing plants will be a potent reminder that sulfur is very much a part of a healthy plant.

When yellow sulfur burns, the sulfur is converted to sulfur dioxide (SO_2), a gas that has a choking, stinging effect if inhaled and is useful as a refrigerant in automatic ice boxes. In the plant, some of the sulfur is built into cystine, an amino acid that forms protein. In the soil, the sulfur may be oxidized and then combined with basic ions such as calcium, potassium and ammonia to form sulfates.

One of these sulfates is calcium sulfate, or gypsum (also called land plaster or "plaster"). Legend has it that Benjamin Franklin spelled out the word "gypsum" on a hillside in Pennsylvania with calcium sulfate, and for a time it stood out in bold contrast because the plants it affected were stimulated in growth. At a later date it was reported that the word could still be seen, not because the plants were making better growth, but because they were making poor growth where the gypsum had been added. Probably the increased plant growth following the application of gypsum had

exhausted the soil of other plant-food elements such as potassium and phosphorus until it was less fertile than if it had been untreated. It would have been interesting to have had these plants examined for nutritional-starvation symptoms.

Another common sulfate is ammonium sulfate, a by-product of the steel, coke and gas industry. It is used as a fertilizer primarily because it contains 20.5 percent nitrogen in the ammonia form, but in fact it also contains 25 percent sulfur. The superphosphates made by the sulfuric acid process contain much sulfur in the form of calcium sulfate. Some potash is produced and used as a fertilizer in the form of potassium sulfate. Thus, sulfur has found a free ride back to the soil. The cost has usually been charged to the other plant-food nutrients that acted as carriers.

Rain also returns to the earth as much as 10 pounds or more of sulfur per acre annually. This has to be picked up as a gas by the atmospheric moisture from smoke produced by the burning of fuel that contained some sulfur. In regions where little or no sulfur-containing fuel is burned, sulfur for plant use may be deficient. Decaying organic matter also releases small quantities of sulfur into the air.

Plants that have insufficient sulfur show characteristic symptoms that may resemble those of nitrogen starvation.

Magnesium

Ordinarily most crops contain more calcium than magnesium. The difference will vary with the crop and the composition of the soil.

We owe the beauty of a green world of vegetation to magnesium. It is the key element in the molecule of chlorophyll—the green pigment in plants that traps the energy from the sun and makes plant life possible. This pigment starts the chain of events that begins with green plants and goes on up through animals and man.

Magnesium is credited with being a companion for phosphates; it combines with phosphates so that the latter can be moved to their proper places in the plants in the form of magnesium phosphate compounds. This bond of attraction still has some mystery about it and must wait for additional research to be better understood.

Calcium

The carbon dioxide in the soil solution makes it a potent solvent for calcium compounds; thus calcium is leached out of the soil as

calcium bicarbonate, and soil acidity is increased. Large amounts of calcium and sodium have been carried into the oceans. Sea water is salty from the accumulation of sodium salts, and it would be milky from the accumulation of calcium salts except for the fact that the calcium has been removed from the water and built into the shells of marine animals to be deposited as limestone on the ocean bottom. This is one of the interesting examples of how calcium is used by animals to build bony material. In plants it is built into the walls of the cells to form a protective "sieve" for the nutrients to seep through in passing into the cells. It also acts as a cement between the walls of the cells to hold them together.

As the cell processes go on to develop the complex substances in the plant, some organic-acid by-products are formed that would be harmful in excessive amounts were it not for the neutralizing effect of calcium. Oxalic acid, for example, is converted to calcium oxalate. The calcium in plants seems to exist in a fine balance with magnesium, potassium and possibly boron. Any upset in this balance due to an excess or a lack of any of them will result in an abnormal performance of plant functions. What may appear to be an excess of calcium in a plant may actually be a lack of one or more of these other elements, and the remedy may be to add the deficient element or elements instead of cutting down the apparent excess of calcium. Similarly, an apparent excess of potassium, magnesium or boron may really be a deficiency of calcium.

Iron

Plants need very little iron, yet it is a most essential element. The top 6 inches of the soil may contain as much as 20 tons or more of iron per acre as iron oxide, Fe_2O_3, yet, on occasional iron-rich soils, plants may starve for lack of this element. In acid soils the iron is usually available to all plants, but in some neutral or alkaline soils it is so insoluble that some plants may have difficulty in absorbing enough. Again, where excessive amounts of soluble phosphates have been added to the soil, the iron may be made unavailable to plants by being precipitated as an insoluble iron phosphate. This may happen in acid as well as in alkaline soils. It is more likely to occur in sandy than in clay soils, because the latter have greater power to fix or "lock up" excessive soluble phosphates.

The chlorosis that develops in plants starved for iron is associated with failure to form chlorophyll, yet it has not been found that iron

is built into this pigment. For the present we must accept the fact that iron is associated in some way with the making of chlorophyll.

Manganese, Boron, Zinc, Copper and Other Elements

These elements have sometimes been called the minor elements because they are required by plants only in trace amounts. This does not mean that they are not as vital to the well-being of plants as the other elements discussed, for they are all the word "vital" implies. Fortunately, they occur in sufficient quantities in most soils, but the use of one or another of them is of major importance for some crops on some soils.

A lack of sufficient manganese or boron is most likely to be associated with calcareous or heavily limed soils. When either of these is lacking, the plant is just as handicapped in performing its normal function as when it is starving for any one of the major elements.

Manganese seems to act as a two-handed (double-valence) reception committee, of which zinc and copper are also members, to greet the other nutrient ions as they enter the plant cell and to direct them to their respective positions where they carry out their functions in the plant. Another way to describe this is to say that these minor elements act as catalysts.

Boron seems to be closely related to some function that calcium performs in the plant. Whenever the proportion of calcium to boron in the plant becomes unbalanced because of a deficiency of boron, the terminal parts of the plant fail to develop properly and the other characteristic boron-starvation symptoms become evident. If this calcium-boron balance becomes upset because of a shortage of calcium or an excess of boron, injury to the plant is likely to result. Thus both a deficiency and an excess of boron produce characteristic symptoms.

Zinc has been found to be effective in treating some physiological diseases, but not much is known about its action in plants. It has already been found necessary to use zinc on certain soils, especially those of the Gulf Coast States and California. Upland soils that are low in organic matter have not been found lacking in sufficient copper for plants. The need for copper appears to be associated with high organic-matter content, particularly in the case of peat soils that are alkaline and contain appreciable quantities of ferrous iron.

An important point about the trace elements mentioned and perhaps others is that in quantities larger than the plant needs they are likely to be toxic or poisonous to the plant, yet the actual

quantity may still be small. Excessive as well as deficient amounts will produce certain characteristic symptoms.

ENVIRONMENTAL FACTORS INDUCING SYMPTOMS

It is helpful to think of plants as things that have taken a long time to develop. They are complex systems of life that have evolved slowly from more simple forms. In Nature's laboratory plants had to adapt themselves to competition from other species, as well as to fit themselves in with a lot of external forces such as soil, temperature, light and disease conditions. Through breeding, man has intensified certain aspects of the plant, but basically as it now exists a plant will grow at an ideal rate when every external factor is most favorable for the job the plant has to do within itself. It is this ideal rate we want for the plant. Any departure from this ideal rate concerns our economic interest. Therefore, it is not only shortages or excesses of the vital plant-nutrient elements that concern us, but also any other factors affecting plant growth. Let us consider some of the factors which contribute to the environment of the plant.

ROOT ZONES

The soil is the pantry that dishes out the water, minerals and nitrogen to the plant through its roots. Unfortunately the roots have to grow into this pantry to pick up the mineral nutrients as if they were on shelves. In other words, these mineral nutrients do not move much in the soil solution—only nitrogen as nitrates can move freely in the soil waters. Therefore, if the physical condition of the soil is such that the roots cannot travel everywhere freely, a real starvation can result in a soil that is well stocked in nutrient elements. So do not overlook the importance of this angle (soil structure and drainage) when diagnosing plant nutrient needs.

Nature's way to meet the requirements for an ideal soil tilth was to let organic matter accumulate. Much of man's trouble with his plants is that he has used too many practices that destroy soil organic matter. The sure way for efficient plant feeding is to return a lot of vegetable matter to the soil. That will open all the feeding trails to the roots, and the organic matter in itself is food for healthy and friendly microorganisms that bring insoluble plant nutrients into solution and keep some root diseases in check. Organic matter also improves soil structure in such a way that the available supply of water in soils is greatly increased. There is more magic to organic matter than science has yet proven.

TEMPERATURES

Every farmer knows that spring growth is poor until the soil warms up. This is due in part to the fact that little or no available nitrogen can be made from the proteins in soil organic matter until the soil is warm and full of free oxygen brought into the soil by warm spring rains. Regardless of the soil type or organic-matter content of unnitrated soils, in cool humid climates grasses and grains starve for nitrogen until the soil warms up. Thus nitrogen starvation may and usually does occur as the first limiting nutrient factor over a wide area, even though later in the season nitrogen may become adequate while other factors become limiting.

The air temperature, too, has a profound effect on the plants' performance. On the one hand plants make carbohydrates through photosynthesis, while on the other hand respiration or the burning of sugar goes on both night and day. If temperatures are too high, especially at night when photosynthesis is stopped, so much sugar can be lost as to affect the growth, and especially the yield of starch crops. In one corn field planted too thick for adequate light at the University of Illinois, the rate of respiration in the extremely hot weather of August 1947 was so high that all the lower leaves died for the lack of carbohydrates. The symptom was definitely one of carbohydrate starvation, but looked somewhat like one of nitrogen starvation.

OVERLIMING

Since the solubility of such elements as iron, zinc, manganese and boron is reduced when the pH value of the soil goes above the neutral point (pH 7.0), there is grave danger of inducing a real starvation for these elements by liming the soil in excess of that needed to neutralize the soil acids. It is easy to overlime sandy soils because they need much less lime than do clay or high organic soils of the same pH.

Overliming can also upset the balance of magnesium or potassium inside a plant. If one of these nutrients gets into the plant in too large a dose it cuts down the function of the other and trouble may result from the unbalanced condition. The safe guide is to stay below pH 6.5 when liming.

INSECTS, DISEASES AND MECHANICAL INJURY

Do not mistake the work of the leaf hopper on alfalfa for potash or boron starvation. Root insects, by injuring the roots, may cause

hunger signs of various sorts. Likewise, alfalfa wilt may hurt the plant in such a way that potash starvation symptoms develop. Various corn or grain diseases give symptoms that look somewhat like hunger signs, but closer study will reveal the differences.

The purple color of older corn plants should not be mistaken for phosphorus starvation. Any condition in the corn plant, and to a lesser extent in other members of the grass family, that causes the sugar concentrations to accumulate abnormally will result in the development of purple pigments. The barren corn stalk with no ear for the storage of sugar is a good example. Another example is a leaf that has been broken or partially cut so that the sugars cannot get out of the leaf and a purple color develops.

WHEN DOES SOIL STARVATION START?

Man has become used to certain magnitudes of crop yields that may be merely the result of some limitations imposed by nature. For example, nitrogen starvation on high-organic-content soils in the cool spring before the soil warms up limits total yield. Man with his scientific knowledge is not satisfied with this limitation, so he sets out to correct the starvation that in the past he accepted as unavoidable. We have accepted that a plant grows to a certain size when all the soil nutrients are adequately supplied, when in fact it may be starving for carbon dioxide or even sunlight. So we see that starvation is a relative term. It may be necessary that we accept some starvation since it may not be economic to correct it, but unfortunately we frequently accept starvation conditions that can be readily and economically corrected.

Starvation symptoms usually appear long after hunger actually occurs. Much damage to growth and yield has usually occurred when a specific symptom shows up. Why then read these hunger signs? Because they give you the knowledge of what the troubles are so that in many cases you can correct them at once, and in all cases alter the treatment for the next crop so as to correct the handicaps.

Plant-tissue tests are valuable aids to assist in diagnosing nutrient deficiencies before starvation becomes so severe that the plants show specific symptoms.

A person with the "green thumb" learns to look at all the plants growing in the vicinity of the plant in question. Frequently some weeds show symptoms before the economic crop does (see Appendix). For example, the milkweed shows boron starvation before

most field or fruit crops do. Wild ground cherries show magnesium starvation before corn or grain. Red stems of white clover blossoms indicate phosphate starvation in orchards while green stems can be relied on to indicate adequate phosphate for fruit trees.

Poor growth without any other symptoms may be a hunger sign in itself, especially when the plant is starving for most of the major nutrients to an equal degree.

SOIL ACIDITY

Soil acidity is mentioned here because it greatly affects the behavior and availability of most of the plant nutrients. It is well to understand what soil acidity is and how it is measured.

The principal acid in soils is not hydrochloric, nitric or any other of the common drug-store acids. Such acids are soluble, easily wash out of the soil, and do not accumulate. However, soil acidity is known to increase with prolonged movement of rain water through the soil. This comes about because the main soil acids are themselves the colloidal particles of clay. They are insoluble and accumulate as soil weathering processes continue.

The clays do not wash out of the soils by leaching, but the alkaline ions of calcium, magnesium, potassium and sodium that were fastened (adsorbed) to the surfaces of the clays in the virgin state have become loosened and have been washed down and out of the soil. When the clay particles are saturated with a mixture of calcium, magnesium, potassium and sodium ions, the soil has no acidity and is alkaline—or, as some say, "sweet." (The term "sweet" is incorrect and should not be used.) When these alkaline nutrient elements are leached out they are replaced by hydrogen, the acid element of soil carbonic acid ($H_2O + CO_2 = H_2CO_3$, carbonic acid). The hydrogen is adsorbed to the spots on the clays from which these alkaline elements had been removed, with the result that the clay becomes a hydrogen clay and the soil becomes acidic.

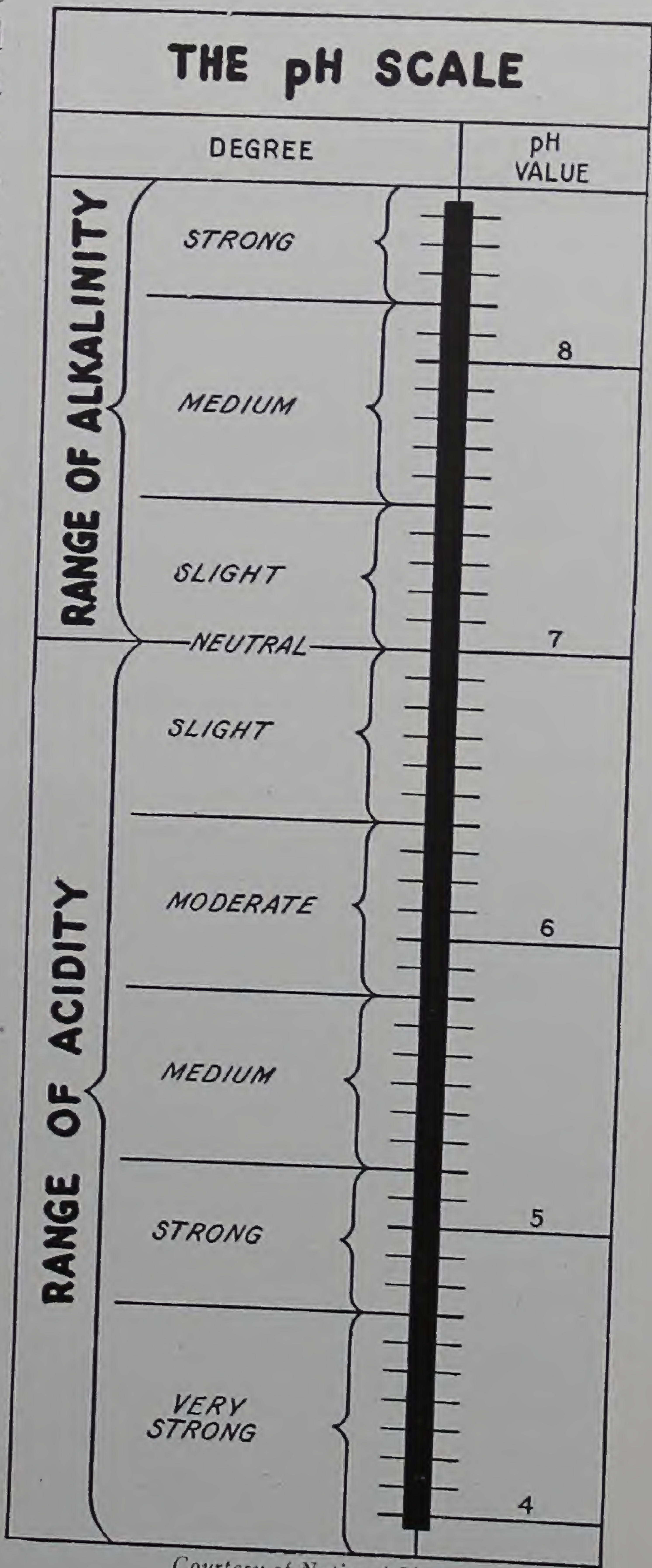
There are other soil acids, too, such as organic acids produced by decomposing vegetable matter, but it is the clay acid that is dominant in acid soils. Since clays in soils are the principal acids, a heavy soil with a great deal of clay would have more acidity to be neutralized by liming than a sandy soil with only a small amount of clay in it.

The strength (intensity) of acids is stated somewhat like the size or gauge of wire, in which the smaller the gauge number the heavier the wire. The gauge of soil acidity is called the pH scale (figure 1).

Here too the smaller the number of the pH value the stronger the acid. Thus, a pH of 4.0 is about the extreme acidity for any soil. A pH of 7.0 is neutral, and above pH 7.0 the soil is alkaline and may contain free lime.

The pH value indicates the intensity or strength of an acid and tells nothing of the amount or quantity that may be present. Let us consider vinegar as an acid. It has a pH of about 2.0 whether you have a quart or a gallon, but it will take four times as much limestone to neutralize a gallon as it will take to neutralize a quart. In a similar way, soils can have the same pH value and still differ greatly in lime requirements. A sandy loam with a clay content of 12 percent would not require much lime to change its acidity from pH 5.0 to 6.5, but a clay loam with a clay content of 24 percent would require about twice as much lime as the sandy loam to produce the same change in pH.

Few crop plants will grow below pH 3.5 or above pH 9.0. The most favorable pH range for most crop plants is 6.2-7.2.



Courtesy of National Lime Association

Figure 1.—The pH scale, showing the ranges of acidity and alkalinity at which crop plants grow.

WHY READ THE HUNGER SIGNS?

Information about the functions of the various nutrient elements in plants has been obtained by scientists largely through carefully conducted experiments in the field, greenhouses and laboratories.

Most of the intensive studies on the fundamental nature of nutrition have been made in greenhouses, with soils in pot tests and with nutrient-solution cultures, in which the plants were grown directly in the solution or on sand or gravel to which the nutrient solution had been added. Field experiments have been used chiefly for testing the practical and economic aspects of fertilizers.

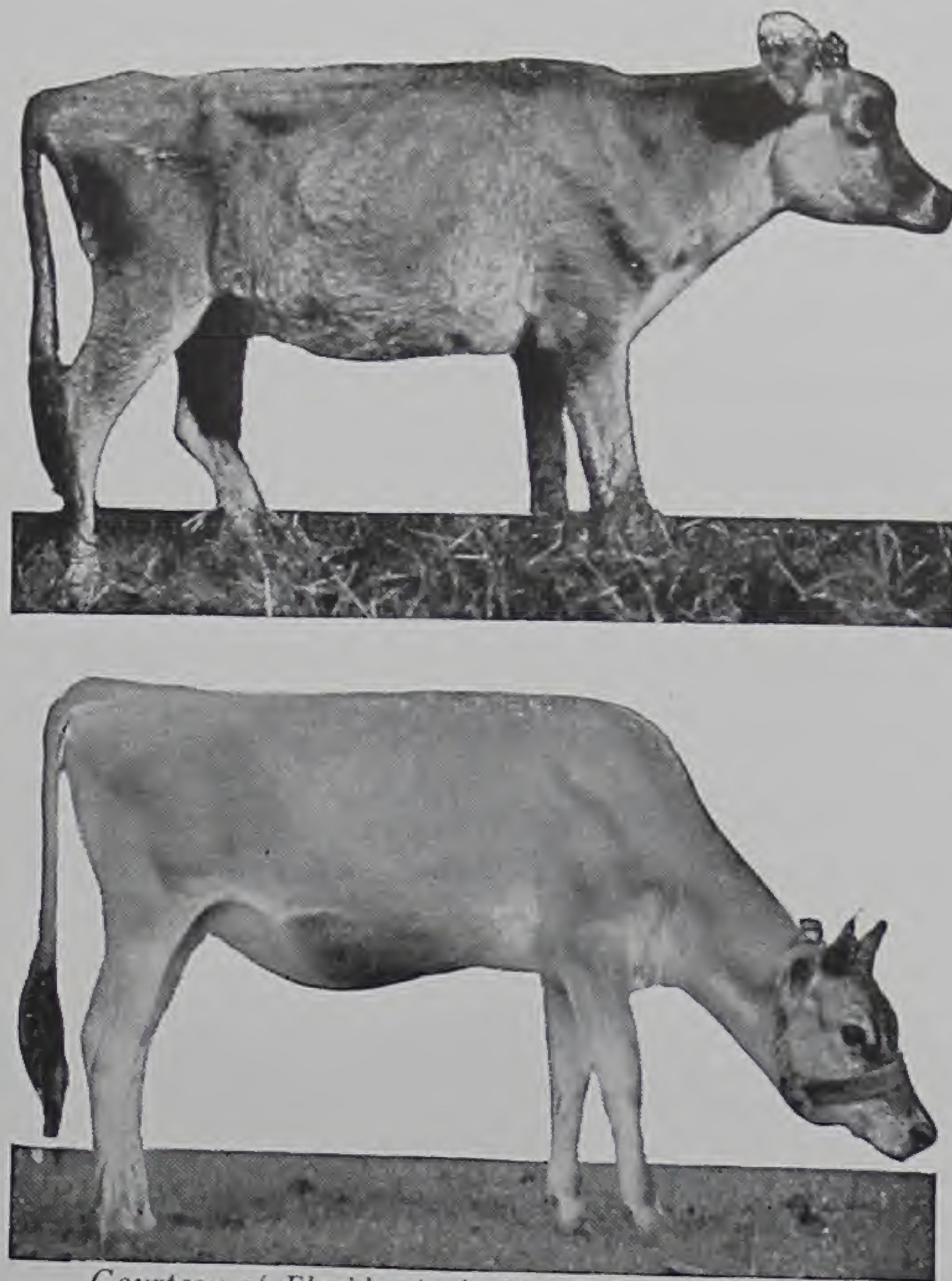
Soil tests have been helpful in diagnosing nutritional deficiencies, and plant-tissue tests have been used in verifying starvation symptoms. The tissue tests are likely to find increased use in the future, for they permit plant growers to detect nutrient deficiencies, particularly in the case of major elements, before the plants show any visible signs of trouble. No grower can afford, however, to disregard the hunger signs that plants show when starving for a nutrient element. The information obtained from the deficiency symptoms requires no laboratory or experiments and is free to anyone who wants to learn what the hunger signs say.

RELATIONSHIP BETWEEN PLANT AND ANIMAL NUTRITION

All animals, including man, are dependent, directly or indirectly, upon plants for their food. Animals fed on mineral-deficient plants

Courtesy of Prof. Paul M. Burson, University of Minnesota

Figure 2.—This cow in northern Minnesota did not have enough phosphorus in her diet.



Courtesy of Florida Agricultural Experiment Station

Figure 3.—Above: An example of nutritional anemia. Below: The same calf after receiving iron-copper supplement and bonemeal. While only a trace of copper is needed by plants it is now known that animals also need this trace.

Figure 4.—A milk cow suffering from cobalt deficiency. Emaciation due to lack of appetite for grain and roughage. Cobalt is not known to be needed by plants, but plants need to contain it to supply the needs of animals.

are poor themselves and the products that they furnish are of low quality.

Cows which graze on lands deficient in phosphorus, for example, lack an essential element—an element they need for healthy bones. The early symptoms are hard to see, but the later stages are plain enough. (See figure 2.)

Cobalt is not known to be needed by plants, but animals produced on feed deficient in cobalt are weak, and they have rough coats and poor muscular coordination. (See figure 4.)

Iodine is another element needed by animals but not known to be needed by plants. However, since most minerals are needed by both plants and animals, the problem of plant and animal nutrition resolves itself into one of simply growing healthy crops.

Courtesy of Dr. C. F. Huffman, Michigan State College

Figure 5.—The same cow as in figure 4, 16 days after starting cobalt feeding

CHAPTER II

Plant-Nutrient Deficiency in Tobacco

By J. E. McMurtrey, Jr.[1]

WHEN the soil does not furnish adequate quantities of the chemical elements necessary for the normal development of plants, it becomes a matter of great importance to supply these elements by means of manures or fertilizers. But first it is necessary to discover some simple, practical method for finding out what elements are lacking.

This can be done by careful observation of the growing plant, which should and does furnish the most direct evidence of its own nutritional condition.

It is possible, of course, to compare the growth of plants by measuring their dry weight, and in fact this is the method that has usually been followed in experimental work. It is not well adapted to the needs of the farmer, however, and in the case of tobacco it does not by any means tell the whole story. With tobacco, the total tonnage produced is not the only thing of importance. Much of the value of the crop depends on that complex and elusive factor, quality. Quality in turn depends on color, aroma, fire-holding capacity, texture, elasticity, body, ability to improve with aging, and other characteristics. Moreover, the qualities required are different for the several so-called types or classes of tobacco—cigar, flue-cured, burley, Maryland, dark air-cured and dark fire-cured. Conditions during growth unquestionably influence the quality of the final product, though it is by no means possible as yet to tell exactly in what ways. There is no doubt, however, that the grower who wants a high-quality product should keep the plants growing normally and during growth watch for signs that something is wrong.

Careful experimental work has resulted in a systematic method of recognizing or diagnosing a shortage of any one of several chemical elements by the symptoms produced in the tobacco plant.

[1] J. E. McMurtrey, Jr., is principal physiologist, U. S. Department of Agriculture, Bureau of Plant Industry, Soils and Agricultural Engineering, Beltsville, Maryland.

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THE BACKGROUND OF DIAGNOSIS

According to modern views (12), the higher plants require the following chemical elements in order to make normal growth, and they require these elements in suitable quantities and forms: Carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, iron, manganese, copper, zinc and boron. The importance of silicon, molybdenum and aluminum in the growth of the tobacco plant under field conditions has not been fully determined, though these elements have been reported by some investigators to be of importance in the growth of other plants.

The elements nitrogen, phosphorus, sulfur, potassium, calcium, magnesium, iron, manganese, copper, zinc and boron are present in varying quantities in agricultural soils. Sometimes they may be present in abundance, but one or more of them may be tied up in chemical compounds that plants cannot readily use. This, of course, is equivalent to a shortage. Decreased growth results when the supply of any one of these elements is insufficient. Since this is true for all of them, it is necessary to watch for other signs besides decreased growth to discover which element is not present in large enough quantities.

These signs or symptoms of mineral hunger in plants may of course be modified to some extent by other factors affecting growth. Light, temperature and the amount and distribution of the water supply all have an influence on growth, and they also affect the total quantity of the chemical elements required by the plant and the rate at which these elements must be supplied. Even under these varying conditions, however, the characteristic symptoms due to the deficiency of an element will be found to be essentially the same.

There are certain other complexities that might be noted at this point.

To say that a single element is deficient is ordinarily the same as saying that there is an excess of other elements in relation to that one. The result is an unbalanced nutritional condition in the plant. It may not always be possible to distinguish between the effects due to the deficiency and the effects due to the relative excess of the other elements. In some cases, too, there may be a large excess of some one element, and this may interfere with the solubility, absorption or utilization of another element to such an extent that acute deficiency symptoms appear, even though there is an abundant supply of the second element. Similar effects may result from the acid-alkaline reaction of the soil (or any other

medium in which the plant is grown). Again, symptoms of poisoning may be added to symptoms of mineral deficiency. Finally, there is the question of what happens when more than one element is deficient. This last, however, is not so complex as it might be, since the visible effects are usually those characteristic of the element that is most deficient.

A deficiency of an element may occur at any time during the life of a plant, and neither its size nor its age alters the effects. As a rule the most typical symptoms are those that show up first, and these are the ones that serve best to distinguish a shortage of one element from that of another. It is not uncommon to observe more pronounced symptoms on one side of the plant or even on one half of the leaf than on the other (11) due to failure of cross transfer of nutrients. After the diagnosis has been made, the practical remedy is usually obvious and more or less easily applied. In most cases, under field conditions it would consist simply in adding the missing element in suitable form to the soil.

Even though the missing element is supplied, however, deficiency symptoms may occur if the element is not supplied in the right amount for the prevailing conditions, or if the conditions are such that it is unavailable for use by the plants. These are points that must be kept in mind by the grower. The tobacco plant has a relatively high content of minerals, as evidenced by the amount of ash that remains after it is burned. Its growth is rapid, and adequate supplies of the necessary elements should be constantly present in the soil.

It should be noted that in practice complete absence of an essential element from the soil rarely if ever occurs. Also, the seeds contain small quantities of the essential elements, and the young seedlings are commonly grown on virgin soils liberally manured and fertilized. Thus it is possible for the young plants to build up small reserve supplies, particularly of the elements that move readily from one part of the plant to another. Finally, commercial fertilizers—and even ordinary "pure" chemicals—usually contain small quantities of various elements as impurities in addition to the elements they are supposed to contain. The plant, then, is always grown under such conditions that, though a given element may be more or less deficient, it is perhaps never entirely lacking.

The most essential requirement for recognizing deficiency symptoms is a thorough knowledge of the plant itself—its life history

and habits, how it looks and how it acts at all stages of growth. It is also necessary to know how diseases and insect pests affect the plant, so their effects may not be confused with the symptoms of plant-food deficiency. The successful grower has this knowledge through long acquaintance with the plant under practical conditions. In fact, once he learns what the deficiency symptoms are, he may be able to recognize them much better than the specialized scientist, who is less familiar with the plant under all the conditions of practical culture.

Because of its large area, the tobacco leaf is an excellent subject on which to study the effects of any environmental factor on growth. Since the plant is produced for its leaf, studies of tobacco leaves during growth may eventually have an unusually important practical application. Most of the symptoms described in the following pages are found in the leaves. Other symptoms could be found, of course, by careful examination of the root or stem.

NITROGEN DEFICIENCY

Under field conditions, the most common deficiency is probably a shortage of nitrogen. As a matter of fact, the nitrogen supply for the tobacco crop must be controlled to produce leaf of a certain type. Some types of tobacco must even be grown under conditions of relative nitrogen starvation—flue-cured tobacco (16), for example, and to some extent burley and Maryland (2, 14). Cigar leaf (17), on the other hand, can be produced successfully only when there is an abundant or luxury consumption of nitrogen by the plant.

Even when tobacco must be grown under conditions of relative nitrogen deficiency, however, the supply cannot be reduced to the proper point until the plant has reached a certain size and stage of maturity. This is apparently an important requirement if the tobacco is to ripen properly.

The plant may show signs of nitrogen deficiency at any period of growth, from the seedling stage to maturity.

The effect first becomes apparent as a decrease in the normal green color. At the same time, growth slows down or stops.

After the first change in the greenness of the plant, the lower leaves turn lemon yellow to orange yellow, the shade apparently depending on the intensity of the green before the nitrogen deficiency occurred. The darker shades of yellow occur on the plants that had the deeper shades of green.

This yellowing is followed by a drying up, or firing, of the yel-

lowed leaves. The number of leaves the plant loses depends on its size and the acuteness of the shortage of nitrogen.

The remaining leaves on the plant tend to assume an erect position, forming an acute angle with the stalk.

The bud leaves tend to retain their normal condition. Apparently their needs are met by a transfer of nitrogen from the older leaves.

If the nitrogen shortage becomes acute at the flowering stage, flowering and fruiting are accomplished by a similar transfer of nitrogen from the older tissues, but the quantity of seed is reduced.

The effects of a deficiency of nitrogen are shown in plate 1, page 47. Here the light-green color of the plant is evident, as well as the yellowing of the lower leaves and the tendency of the unyellowed leaves to stand more upright than usual. (The same symptoms have been reported in plants grown in solution cultures (9) when the supply of nutritive elements was accurately controlled.)

A nitrogen deficiency appears to reduce in some way the water content of the plant. This probably accounts for the fact that a nitrogen shortage and a water shortage sometimes show much the same symptoms. A nitrogen shortage, however, may occur when the plant is standing in water all the time, as in a solution culture.

The effects of a nitrogen shortage can be seen in the cured leaf. Its size is reduced, the amount of reduction depending on the stage at which the shortage occurred. The color is also affected, differently with different types and methods of curing. The flue-cured type of tobacco has the desired lemon-yellow color only when the nitrogen supply is reduced to the point of deficiency at the ripening stage. With the cigar type, nitrogen deficiency is decidedly injurious at any stage; it results in undesirable colors and other poor qualities not well understood. The nitrogen supply is also known to influence nicotine content to a great extent, low nitrogen generally producing a leaf with a low nicotine content.

PHOSPHORUS DEFICIENCY

Practically all tobacco soils except those derived from phosphatic limestones are initially deficient in phosphorus. Phosphorus deficiency, however, causes tobacco plants to exhibit growth effects less characteristic (9, 13, 17) than those resulting from a shortage of any of the other essential elements.

The symptoms that serve to identify the condition are a certain type of slow growth and lack of maturity.

With this stunted growth, the plant assumes a rosette condition. The color is very dark green, as shown in plate 2, page 48.

The size and shape of the leaves are altered (figure 1). The leaves tend to be narrow in proportion to length. Usually there appears to be no abnormality of the leaf other than in size, shape and color, but in a few instances spots have been evident on the lower leaves of the plant as shown in figure 2. These spots do not occur consistently on phosphorus-deficient plants either in the field or in solution cultures.

The leaves form an acute angle with the stalk, as seen in plate 2, page 48.

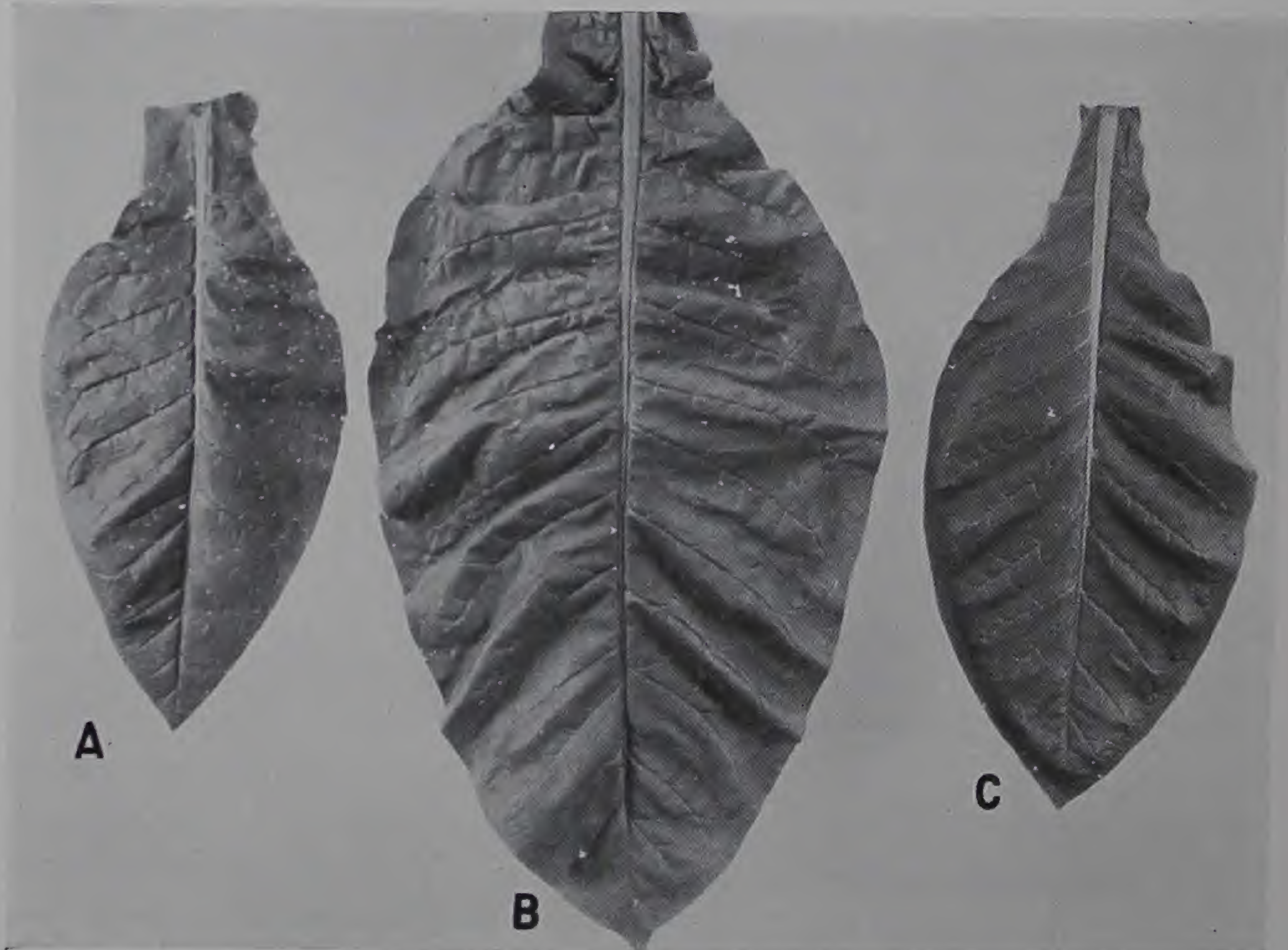

Figure 1.—A and C show the small, rather narrow leaves that result from phosphorus shortage. B is from a plant liberally supplied with phosphorus.

Under field conditions, firing of the lower leaves has not appeared to any considerable extent.

The bud leaves tend to retain their normal appearance, possibly because phosphorus is transferred to them from the older parts of the plant. Similarly, flowering and fruiting are successfully accomplished when the shortage becomes manifest at this stage of growth.

If tobacco is to have the desired quality when cured, it is essential that the leaf reach a certain stage of maturity before harvest. Leaves from plants suffering from phosphorus deficiency are immature and therefore have an undesirable quality. The cured leaf tends to be dark brown, dark greenish or black. The crop is also frequently delayed until late in the season, when the weather is unfavorable for curing, especially in the case of the air-cured types.

Figure 2.—Leaf spot such as this sometimes occurs as a result of phosphorus deficiency.

POTASSIUM DEFICIENCY

Tobacco requires a great deal of potassium; in fact, what would be a luxury consumption from the standpoint of yield alone seems to be necessary to produce leaf of high quality. The plant shows striking symptoms when potassium is not present in adequate quantity (1, 9, 13, 17, 18), though under field conditions the reduction in growth is not so marked as in the case of a shortage of nitrogen

or phosphorus. Many tobacco soils do not supply sufficient amounts of potassium for normal growth, and probably the first deficiency effects reported for tobacco were those due to a deficiency of potassium. The deficiency symptoms tend to be aggravated by dry weather.

The lower leaves of the tobacco plant suffering from potassium hunger show a typical mottling, or a loss of green color (chlorosis) at their tips and margins, as shown in plate 3, page 49.

This is rapidly followed by the development of specks of dead tissue (necrosis), usually as small spots in the center of the mottled areas.

Figure 3.—This plant, from a seedbed, shows that even seedlings may be affected by potassium hunger.

Later the areas of dead tissue may enlarge and run together to such an extent that most of the leaf tissues between the veins are involved. As the dead areas enlarge and involve more and more tissue, they dry to a brown color, so that the whole plant comes to have a brownish or rusty appearance. The parts of the leaf that remain green are darker and more bluish than normal.

The dead areas may fall out, producing a ragged appearance of the leaf, as shown in plate 4, page 50.

Even before the mottling and the appearance of dead spots, the leaves become cup-shaped from the under side. Probably this is because growth slows down at the edges but continues in the center, so that the margins seem to roll inward and downward. This crumpled effect becomes more marked as the living tissue continues to grow around the mottled and dead areas.

The mottling appears to progress rapidly from the lower to the upper leaves.[2] There may be some loss of the older leaves, but this is not characteristic as it is in the case of nitrogen deficiency.

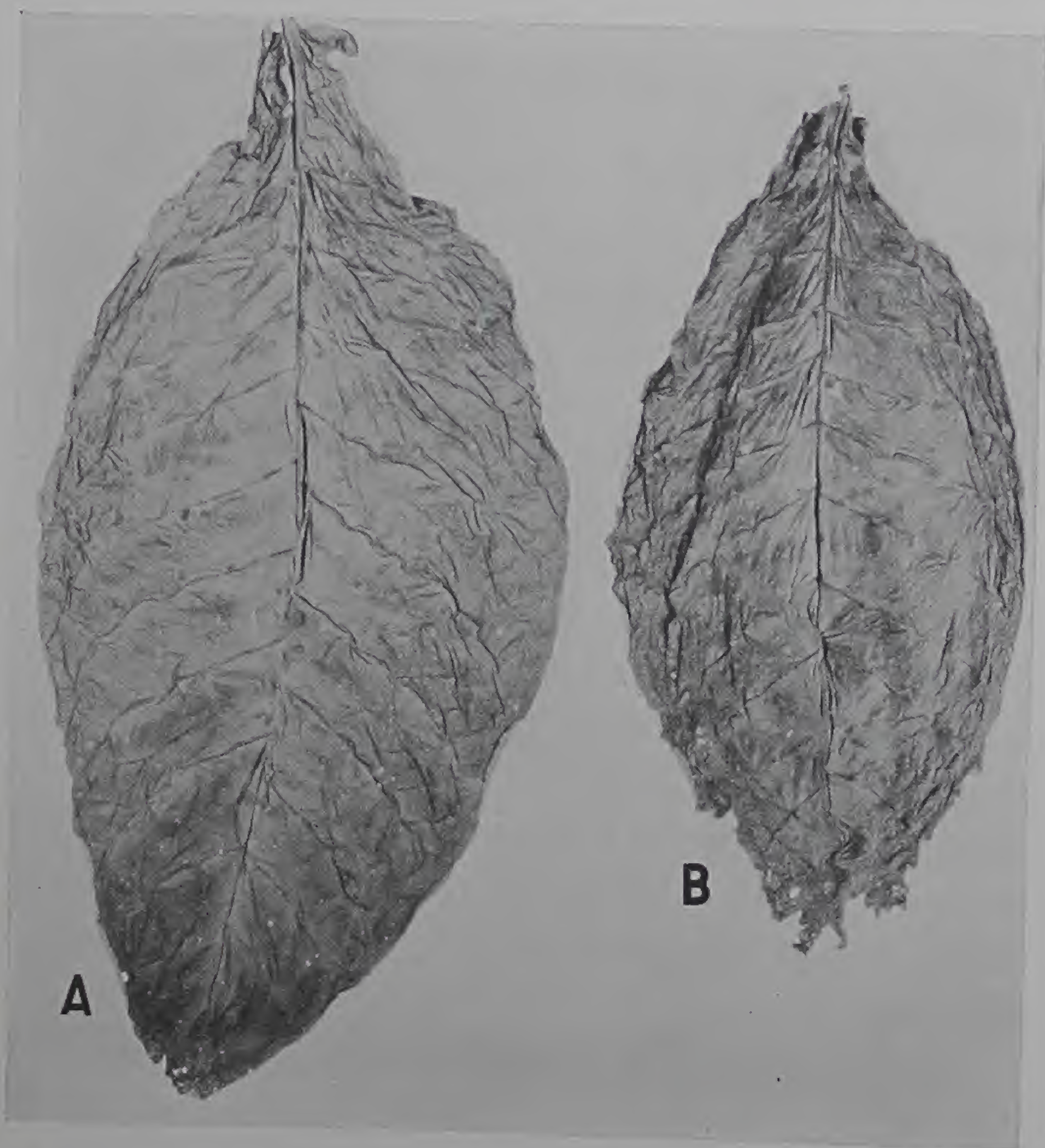

Figure 4.—Cured leaf, Maryland type. B shows reduced size and ragged appearance due to potassium hunger. A, cured leaf from a plant liberally supplied with potash.

In all cases observed, the bud leaves tend to retain their normal appearance, apparently because potassium is transferred to them from the older parts of the plant.

Symptoms of potassium hunger may be observed on young seedlings from the seedbed (figure 3) as well as on the large plants in the field.

It has been consistently reported that under field conditions a liberal supply of potassium enables the plant to withstand or ward

[2] In rapidly growing plants in the field, after the lower leaves are almost mature the upper leaves may show the mottling and spotting without the lower leaves showing any decided symptoms.

off attacks of leaf spot caused by bacteria (14, 16, 17). Perhaps under conditions of shortage the development of dead areas, already described, allows the organisms causing certain leaf-spot diseases to enter the tissue at these points. This would hasten the breakdown of the tissue.

It is well recognized that in some manner potassium aids in maintaining the general vigor of the plant. There appears to be a relationship between potassium and nitrogen in this connection. With cigar tobaccos, grown under high-nitrogen conditions, it is difficult to obtain the protective action of potassium found with Maryland and flue-cured types, where the nitrogen supply is purposely limited.

In the cured leaf, potassium shortage is shown by reduced size and a ragged appearance, as illustrated in figure 4-B. The cured leaves are off type in color, though they do not show the distinctive color patterns described for the growing leaves. They also lack body, elasticity, aroma and ability to condition when exposed to moist air, and they have a poor fire-holding capacity.

MAGNESIUM DEFICIENCY

Magnesium deficiency has been given the common name of "sand drown" (3, 5, 9, 13, 16, 17) since it is most prevalent in deep sandy soils and during seasons of excessive rainfall. The deficiency symptoms rarely appear in the field until the plants have attained considerable size, more commonly after topping when the growth rate is rapid. Thus the leaves usually attain almost normal size and shape. Other symptoms of magnesium deficiency, however, are very striking.

Since magnesium is part of the chlorophyll molecule, the green pigment is affected when the magnesium supply is short. The loss of green color commonly progresses in a definite manner.

First, the lowermost leaves of the plant lose their normal color at the tips and margins (plate 6, page 51) and between the veins. The color may vary from a pale green to almost white, depending on the acuteness of the shortage. The veins and the tissue close to them tend to retain the normal color long after the rest of the leaf has lost practically all its green pigment. Even in extreme cases, when the lower leaves become almost white, they rarely dry up or develop dead spots.

The loss of color characteristic of magnesium hunger proceeds uniformly, as a rule, from the base of the plant upward (plate 5,

page 50).[3] On the individual leaf, it begins at the tip and margin and proceeds toward the base and center. The yellow as well as the green pigments appear to be affected. The entire area of the leaf and all the leaves of the plant may be involved in extreme cases, though the bud tends to remain normal.

The contrast between the pale and the normal tissue is sharp-

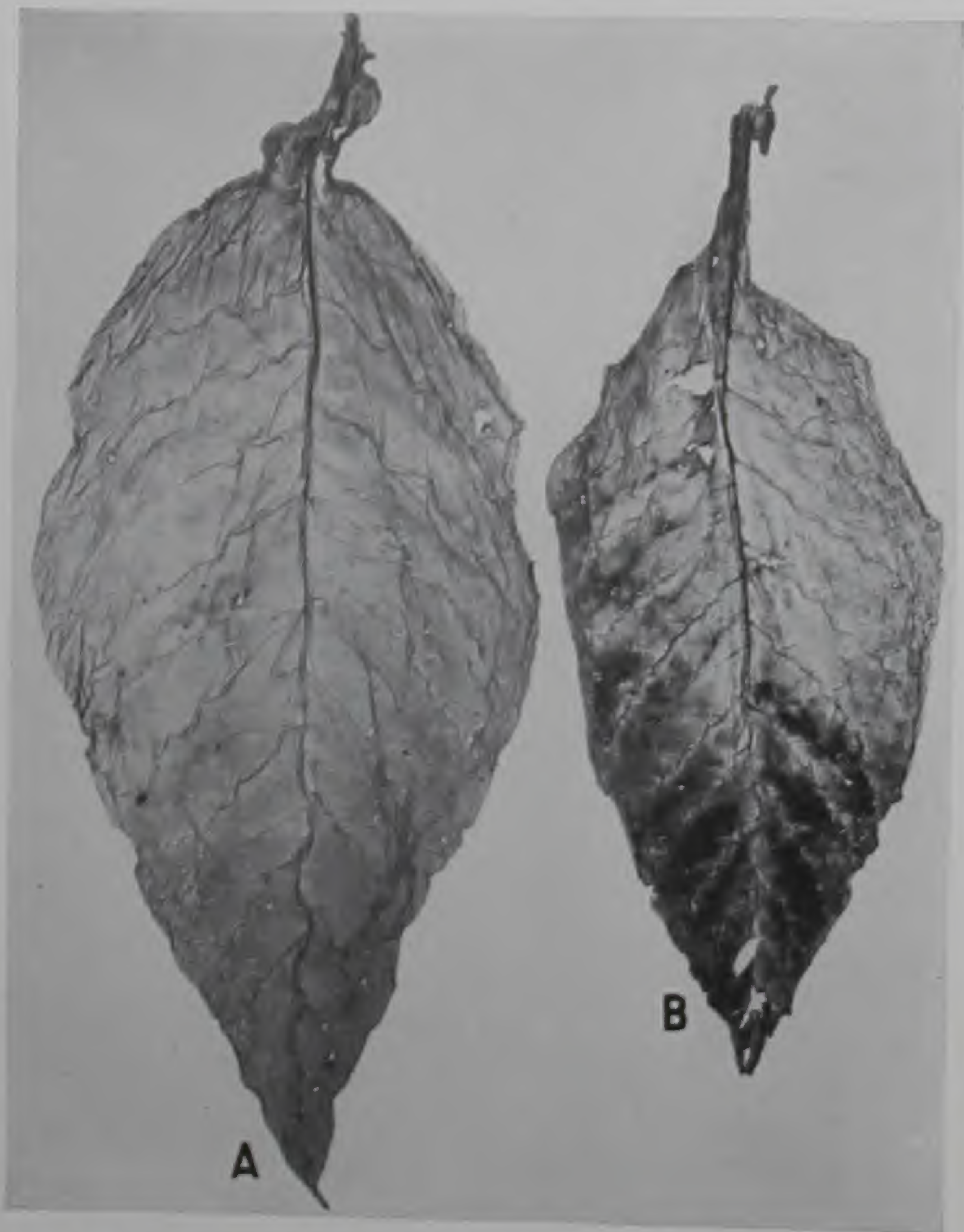

Figure 5.—Flue-cured tobacco leaves. B shows dark, irregular patches and other signs of poor color due to magnesium deficiency. A is from a normal plant.

est in plants with a dark-green color. It is not so striking when the plant is light green in color because of a low supply of nitrogen or sulfur.

It was pointed out above that symptoms of magnesium deficiency usually appear when the plant has attained considerable size. They

[3] Under experimental conditions, in solution cultures, some of the old lower leaves may not lose their green color when the plant is growing rapidly and magnesium is suddenly withdrawn. Also, in solution cultures the appearance of dead spots even before loss of color has been reported. This spotting has also been observed in plants grown in soil cultures in the greenhouse when the soil was leached with an excessive amount of nutrient solutions lacking magnesium. It has not been observed to any extent in field cultures, but it might possibly occur with rapidly growing plants under excessive rainfall.

have been observed, however, even in the seedling stage, as plate 7, page 52, shows. The extent of the dwarfing that results from a magnesium shortage seems to be simply a question of when the shortage operates and how acute it is. The yield is reduced to the extent that dwarfing occurs, but as already noted this may not be severe if the shortage becomes acute only at a late stage of growth.

The reduction in the quality of the cured leaf is more serious. It is indicated by dark and irregular colors, loss in weight, dry leaf

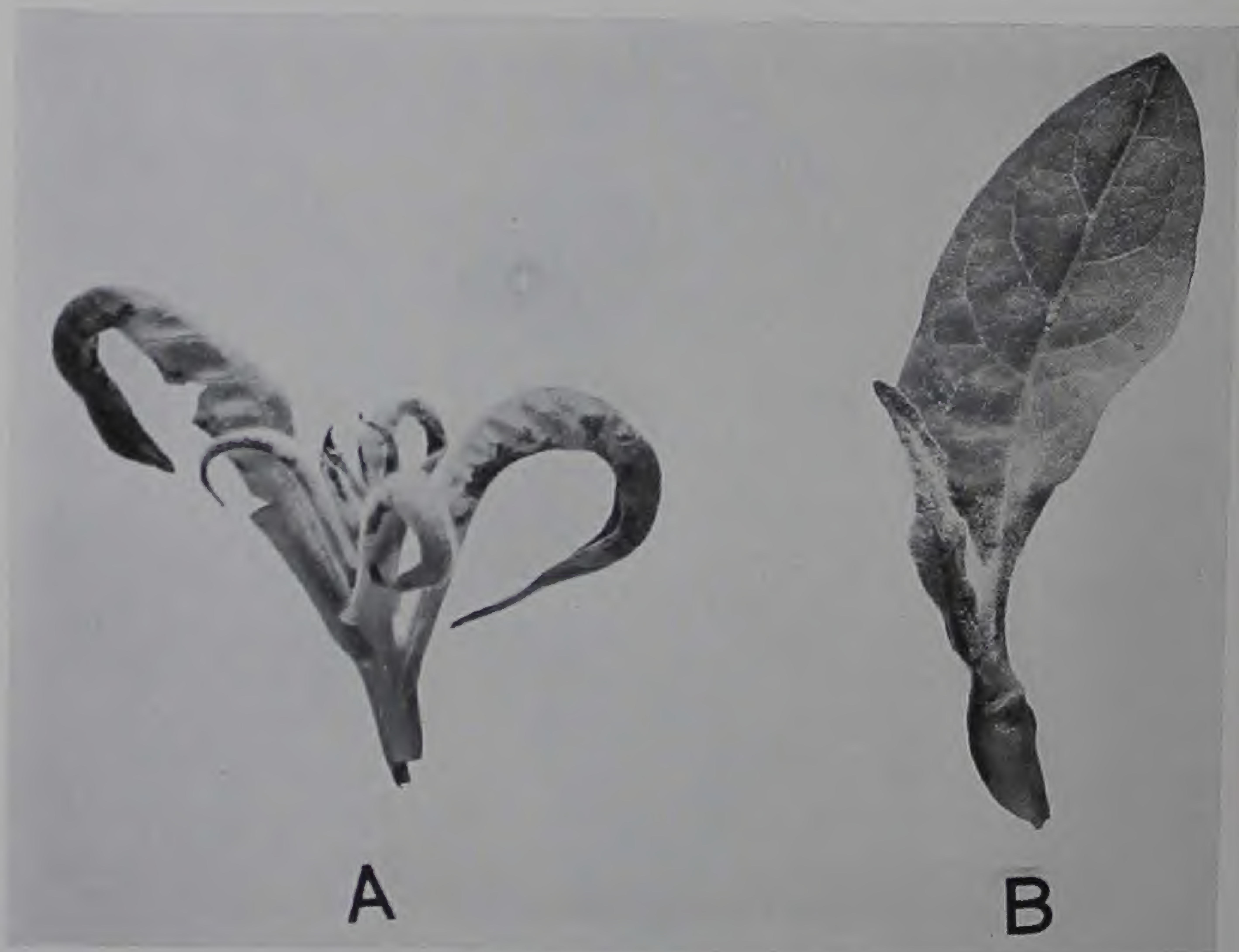

Figure 6.—Terminal growth affected by mineral deficiencies. A, the first stage of calcium shortage; note the hooking downward of the bud leaves; B, an early stage of boron deficiency—breakdown of tissues at the base of the leaf.

tissues and a lack of body and elasticity. These signs of lowered quality are more evident in the flue-cured (figure 5) than in the air-cured types of leaf. It has been reported that magnesium is an important constituent in cigar tobacco and that when the magnesium content is low, the ash tends to be dark in color.

CALCIUM DEFICIENCY

Calcium has long been recognized as an essential plant nutrient, but it has been erroneously assumed that all agricultural soils contain

enough of it for strictly nutritive purposes. It is commonly used, in the form of hydrated lime or calcium carbonate, not as a food for plants, but to bring about the best soil reaction for plant growth. The ions, or small electrified particles, of calcium may be said to antagonize the ions of objectionable substances, or to neutralize or render them harmless. It is quite probable, however, that in some cases favorable results are also due to the nutrient value of the calcium.

When the calcium supply is deficient (4, 9, 13, 17) the tobacco plant shows distinctive abnormalities in growth. Just what form

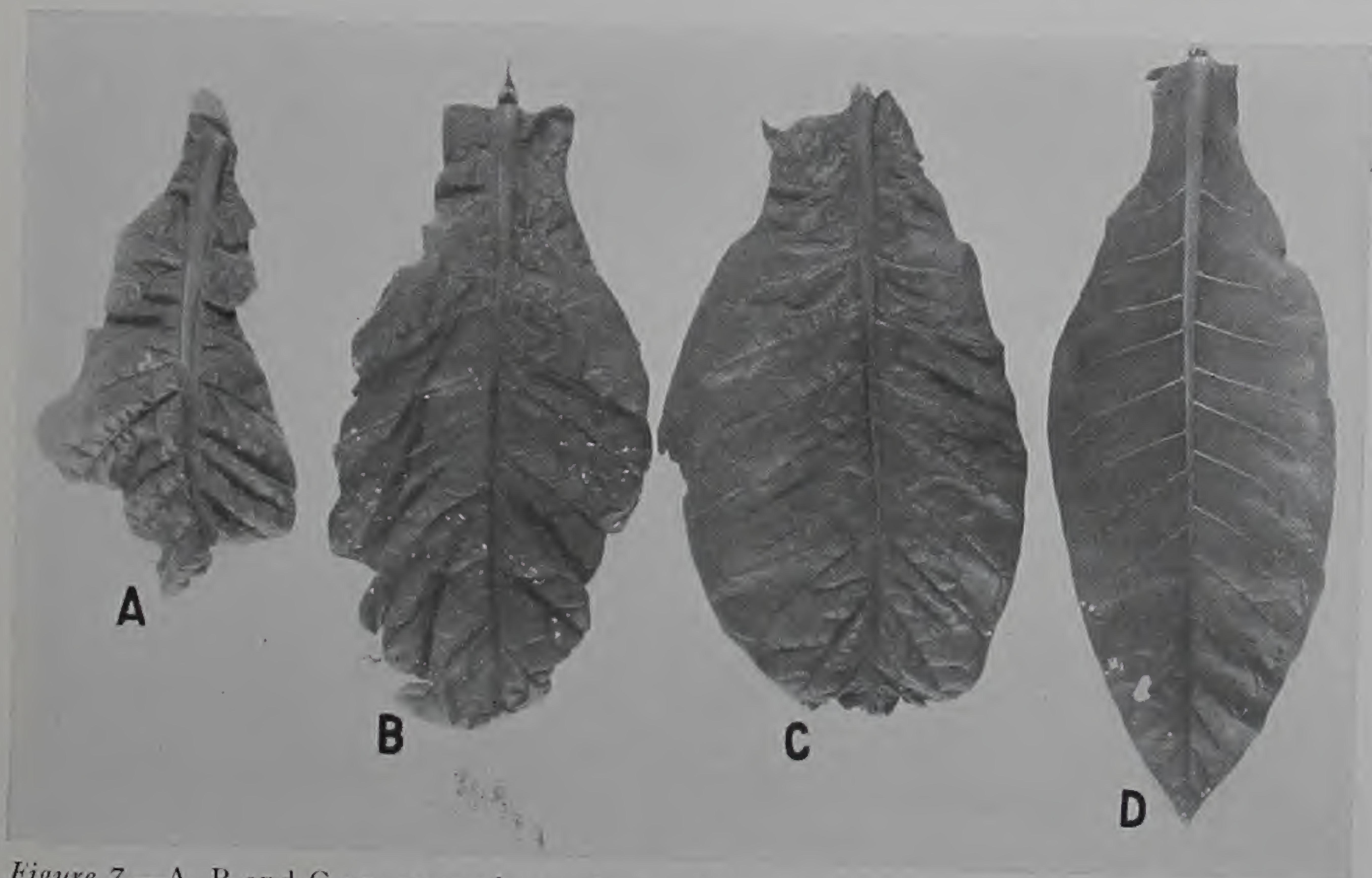

Figure 7.—A, B and C are young leaves from a tobacco plant showing the scalloped, irregular edges due to calcium deficiency. D is from a normal plant.

these abnormalities take seems to depend to some extent on what other substances are present under a given set of conditions. This is in keeping with the function of the calcium ion as an antagonizer of other ions. Magnesium gives the most striking illustration of this relationship. Quantities of magnesium that produce normal growth in the presence of calcium seem to become poisonous in its absence. What happens in this case is typical, for all practical purposes, of calcium deficiency in general.

The first symptom of calcium deficiency is the development of a light-green color, followed by a peculiar hooking downward at the tips of the young leaves making up the terminal bud (figure 6-A). This is followed typically by the death of the young leaves, which

break down first at the tips and margins. If complete breakdown does not occur and growth takes place later, portions of the tips and margins of the affected leaves are missing, and this gives them a scalloped appearance (figure 7). As the illustration shows, they are also distorted. The older leaves, however, may be normal in shape (plate 9, page 53).

The plant as a whole is abnormally dark green. In the later stages of extreme calcium shortage, the terminal bud dies. This is

Figure 8.—Tobacco plant after recovery from a calcium shortage in dry weather. Note that the young leaves at the top have grown normally.

equivalent to topping, and it results in a thickening of the older leaves. In some cases of acute shortage, dead spots may develop and loss of color may occur on the older leaves, though these effects have rarely been observed.

When lateral shoots or suckers begin to develop in the leaf axils after the death of the terminal bud, their terminal growth in turn goes through the same stages, and the buds die.

These effects were first reported on plants grown in solution cultures, and later they were found to be typical in the field.

The topmost leaves sometimes show no abnormality (figure 8) when deficiency symptoms are evident on the middle leaves. This appears to occur in dry periods, when the roots may have penetrated to greater depths than usual, enabling the plant to draw on subsoil reserves of calcium.

A symptom that has been experimentally reproduced by adding excess manganese in the presence of calcium has sometimes been observed in the field. The young leaves lose color and then develop

Figure 9.—Effects of calcium shortage on flowering parts of tobacco. Note (B) the drying up of the corolla and the distortions of the calyx. A is from a normal plant.

dead spots. In the experimental work, the condition has been corrected by the application of limestone.

In the case of plants grown in the greenhouse, the floral parts show striking effects if the calcium shortage does not become acute until the flowering stage. In figure 9, A shows the floral parts from a normal plant and B those from a plant grown under conditions of calcium shortage. In plant B there has been a tendency to shed blossoms and buds, and the flowers that remain show a dieback of the corolla, with the pistil protruding. In most cases there

are spots of dead tissue on the calyx lobes. This condition has been observed commonly in the field.

It is evident from these various symptoms that there is little or no transfer of calcium from the older tissues to the growing points, as there is in the case of the older elements previously described. This means that if normal growth is to occur there must be a continuous supply of calcium available to the plant.

The effects of calcium deficiency on growth are disastrous to the cured leaf. The malformation and thickening of the leaf, the death of the terminal bud, and the other physiological disturbances combine to produce a tobacco of extremely poor quality.

BORON DEFICIENCY

The effects of boron starvation on plant growth had been reported in experiments with solution cultures (8, 9) some time before they were recently recognized under field conditions (7, 10, 17).

An acute boron shortage first produces marked changes in the tip or growing point of the plant.

The young leaves of the terminal bud become light green in color—paler at the base than at the tip. They also show a somewhat drawn appearance. When these symptoms appear, the leaves have already ceased to grow.

Next, the tissues at the base of the young leaves show signs of breakdown (figure 6-B). If growth should take place later, before all the tissues are broken down, these leaves would be distorted by the growth around the injured tissue. Usually they have a one-sided or twisted appearance. The stalk toward the top of the plant may also show a distorted or twisted type of growth.

The death of the terminal bud (plate 10, page 54) follows these stages. This automatically tops the plant, causing the leaves to thicken and increase in area. The upper leaves tend to roll in a half-circle downward from the tip toward the base. They are abnormally light in color and become smooth, stiff and brittle. When the midrib or secondary veins are broken, their vascular tissues show a dark discoloration.

Lateral buds (suckers) may develop in the axils of the leaves or at the base of the stalk, but they typically break down like the terminal bud.

When boron shortage does not become acute until the flowering stage, the flower buds are shed and no seed pods are set.

These symptoms would indicate that there is little or no transfer

of boron from the older plant parts to the younger growing points. Therefore a continuous supply must be available for normal growth. Only a very minute amount or trace of boron, however, is needed or even tolerated by the plant. Any considerable amount acts as a poison.

It has not been possible to make extensive observations of the effects of boron deficiency on the cured leaf. From the observations available, it is evident that marked effects are to be expected in view of the striking modifications in growth produced by boron shortage.

MANGANESE DEFICIENCY

When tobacco plants apparently manifesting a new disease were submitted to the Department of Agriculture by a grower, it was possible to identify the symptoms as those of manganese hunger because the same symptoms had been produced experimentally in sand and solution cultures. Later the identification was substantiated by field trials on the area from which the plants were taken.

Distinctive symptoms of manganese shortage, however, have been reported in only a few cases in the field. Perhaps they are rare because this deficiency is usually associated with a neutral or alkaline soil reaction. Such a soil reaction favors the black root-rot disease (*Thielaviopsis basicola* (Berk. and Br.) Ferraris), which limits growth and would tend to hide the effects of a shortage of manganese.

The first visible symptom of manganese hunger (9, 13, 15, 17) is a loss of color in the young leaves. This loss of color follows out the minutest branches of the veins, or vascular system. Between the veins the tissue is light green to almost white (plate 8-3, page 52), while the veins themselves remain darker. The leaf has a checkered appearance because of the contrast between the green veins and the tissues that have lost their color.

The loss of color is followed by the development of spots of dead tissue, which may drop out, giving the leaf a ragged appearance. Usually this spotting is not confined to the tip and margins, as in the case of potassium deficiency, but involves parts scattered over the entire leaf.

The plant as a whole may be considerably dwarfed (plate 11-2, page 55), and in general appearance it is light green.

The cured leaves from plants affected by manganese shortage are of decidedly poor quality. The most apparent effects are the dead

spots and the lack of desirable color (plate 12, page 55). The leaf also lacks body, elasticity and aroma.

SULFUR DEFICIENCY

Tobacco plants suffering from sulfur deficiency have not often been found under field conditions (13)—chiefly, perhaps, because most commercial fertilizers contain an ample amount of sulfur, many of their common ingredients being high in this element. In addition, the rainfall in the tobacco-growing regions usually brings down considerable quantities of sulfur. In fact, sulfur deficiency becomes evident in dry periods, when the shortage is produced intentionally.

The first evident symptom is the light-green color of the plant as a whole, though there is a tendency for the young leaves to be lighter than the older ones. (In solution cultures (9) the light-green color is largely confined to the younger leaves.)

The plants do not lose their lower leaves by firing, as they do in the case of nitrogen shortage. This fact serves to distinguish the two deficiencies.

In Georgia and South Carolina, some blistering of the leaves has been associated with sulfur deficiency in the case of flue-cured tobacco.

There may be some reduction in growth and frequently there is a characteristic crimping downward of the leaves at the tips (plate 13, page 56).

As a rule, the effects of sulfur deficiency have been apparent under field conditions only in the early stages of growth. They are evident only during dry periods, and recovery has been observed to take place rapidly and completely when rain occurred. Apparently the rain supplies the needed sulfur.

The cured leaf of plants suffering from sulfur shortage shows color effects that are sometimes desirable and sometimes undesirable. In the case of flue-cured leaf, a sulfur deficiency may be advantageous, provided yields are not seriously reduced; it produces more desirable colors than an overabundance of sulfur. In Maryland leaf, on the other hand, an abundant sulfur supply produces the more desirable colors.

IRON DEFICIENCY

As yet, iron deficiency has not been observed in tobacco under field conditions. It has been reported as occurring in plants (6) other than tobacco, however, and it is worth while to describe the

symptoms produced experimentally in tobacco (9, 13, 15) grown in sand or solution cultures. In the case of plants other than tobacco, the deficiency is associated with neutral or alkaline soils. This might account for the failure to find it in field-grown tobacco, since the situation would be complicated by the root-rot organism mentioned in the case of manganese deficiency.

A leaf of a tobacco plant grown experimentally under conditions of iron shortage is shown in plate 8-1, page 52. It will be observed that the leaf is suffering from chlorosis or loss of green color. This is typical of other plants affected by iron deficiency, and in fact for a long time it was the only recognized type of chlorosis occurring in plants.

As shown in plate 14, page 57, the loss of color first becomes evident in the young or upper leaves (9, 13, 15) of the tobacco plant. The leaves making up the terminal bud lose color between the veins and become light green or white. In extreme cases the veins also lose their color and the whole terminal bud may turn almost white. Usually, however, the principal veins tend to retain their color, as do the lower leaves of the plant.

The affected leaves characteristically show no breaks or areas of dead tissue, though sometimes they dry up. Apparently this occurs under conditions of bright sunlight and dry air.

The fact that the growing point is immediately affected indicates that iron is not transferred from the older parts of the plant and that a continuous supply must be available if growth is to be normal.

COPPER DEFICIENCY

As in the case of iron, symptoms of copper shortage have not yet been observed in tobacco under field conditions, though they have been observed in other plants. Since they have been associated with soils high in organic matter, like those on which tobacco is sometimes grown, it seems worth while to describe the effects of copper hunger on tobacco plants (15) grown experimentally in the greenhouse.

As figure 10-B shows, the upper leaves are unable to retain their turgor or rigidity, so that they wilt badly. Such plants are permanently wilted; they do not recover at night or during cloudy periods like plants that have wilted on a hot day.

There is a reduction in growth in proportion to the extent of the copper shortage and the stage of growth at which it operates.

When a copper deficiency becomes evident during the flowering

stage, the seed stalk does not stand erect and the amount of seed is reduced.

Copper is one of the elements needed by plants only in very small amounts. In nutrient solutions, the amount needed to correct a deficiency was found to be from one-sixteenth to one-eighth part per million—equivalent to half an ounce of copper in some 30 to 60 thousand gallons of water. Amounts in excess of these small quantities produced a decided stunting of the plants.

Figure 10.—Effect of copper deficiency on growth of tobacco. A, normal plant grown in nutrient solution with copper added; B, plant grown without copper—note the extreme and permanent wilting of the upper leaves.

Under field conditions, the amount to be applied would depend on the fixing power of the soil for this element. The chemical situation would seem to make it inadvisable to include copper compounds in standard fertilizer mixtures at least until there is evidence

that copper is deficient in a wide variety of soils, since the phosphates would combine with copper to form cupric phosphate, which is relatively unavailable for use by plants because it does not easily dissolve. In case of deficiency, it may prove best to apply the copper as a spray directly on the plants.

ZINC DEFICIENCY

Zinc is another element not known to cause deficiency symptoms in field-grown tobacco. However, there is a disease of tobacco, occurring in wet periods, characterized by a leaf spot commonly attributed to bacteria. It causes a breakdown of the leaf (14, 16), and frequently a large part of the crop is severely damaged. The symptoms correspond in many respects to those produced experimentally by a shortage of zinc. It is not possible to say with certainty as yet whether zinc deficiency is a factor in this disease.

Striking effects are produced in the plant (15), as shown in plate 15, page 58, when zinc is withheld in sand or solution cultures.

Typically, the lower leaves first show a slight loss of color at the tips and margins. This is followed by the development of areas of dead and broken-down tissue. Usually a small area is involved at first, and in some cases this area is surrounded by a halo such as has been reported for leaf spots produced by bacterial inoculation.

In most cases the dead areas, which at first have a water-soaked appearance, spread rapidly. Frequently an almost total collapse or death of the leaf tissue follows in a very short time. The breakdown may come so quickly that the early stage, characterized by loss of color, may not be evident. Sometimes, too, the lowermost leaves of the plant are not the only ones involved.

The small veins are not involved at first, but frequently they also soon break down.

As a rule, the dead leaf tissue finally dries to a brown color.

There is some shortening of the internodes—the spaces between the leaves on the stem—and the green leaves appear to be thickened.

It will be noted that in some ways these symptoms resemble those described for potassium hunger. There are distinct differences, however. In the case of potassium shortage, the first breaks or lesions in the tissue are more sharply confined to the leaf tips and margins; the small veins do not ordinarily break down at all; and the breakdown proceeds much more slowly.

As in the case of copper, it does not appear advisable at present to include zinc in fertilizer mixtures. Zinc would combine with

soluble phosphates to form zinc phosphate, which cannot readily be dissolved, particularly in alkaline soils. The use of small amounts of zinc is sometimes desirable, but spraying seems to be the most practical method of application. In any considerable amount, zinc is poisonous to most plants.

RECOGNIZING COMPOUND DEFICIENCIES

In practical plant culture, where the causes of an abnormal condition cannot be determined from the nature of the treatment given the soil as they can be in experimental work, it is necessary to make an accurate diagnosis from the symptoms alone. For this reason, various combinations of mineral deficiencies were tried out under field conditions to see what the symptoms would be under these circumstances. Not all the possible combinations have been tested, but so far, with a single exception, there has been little or no blending of symptoms; the visible effects have always been those of one deficiency which appeared to dominate the rest.

This should simplify the problem of diagnosis and treatment. If there should be more than one deficiency, the dominant one can be recognized and corrected, then the next that appears, and so on.

When potassium, calcium and magnesium were withheld, the symptoms were essentially those of potassium deficiency, though the reduction in growth was more extreme. When the potassium shortage was corrected, the plants still showed a marked reduction in growth, but the other symptoms were those of magnesium shortage alone, without any signs of calcium deficiency.

On untreated plots without any added fertilizer, the plants usually show the symptoms of nitrogen deficiency. In some cases, however, the dominant symptoms have been those of potassium deficiency alone, or phosphorus deficiency alone, or even sulfur deficiency alone.

The one case of blended symptoms so far observed occurred with a combined shortage of magnesium and sulfur, experimentally produced. Here, the sulfur shortage gave the plants a light-green color and, as already pointed out, this tended to mask the striking color pattern ordinarily produced by magnesium hunger.

A COMPARISON OF SYMPTOMS

So far, the symptoms produced by these mineral deficiencies have been described one by one. It has already been said that the symp-

tom common to all of them, though it may be more marked in some cases than in others, is reduced growth. This is clearly shown in figure 11, in which a normal tobacco plant is placed beside six abnormal plants, each affected by a different deficiency.

The symptoms other than reduced growth will now be compared to bring out the differences between them.

The first thing that strikes the observer making such a comparison is that the symptoms of mineral shortage can be classified into two broad groups.

Figure 11.—Tobacco plants suffering from various mineral deficiencies—B, nitrogen; C, phosphorus; D, potassium; E, boron; F, calcium; G, magnesium. Reduction of growth has occurred in all cases. A is a normal plant.

In one group, it is primarily the older leaves of the plant that are affected. This is the case with deficiencies of nitrogen, phosphorus, potassium, zinc and magnesium. Apparently, when there is a deficiency of one of these elements in the soil, the element can be readily transferred from the older parts of the plant to the young growing parts, so that the new growth does not show deficiency signs.

In the other group, it is primarily the new growth and young leaves that are affected. This occurs with deficiencies of calcium, boron, sulfur, iron, copper and manganese. The elements apparently cannot be moved readily from one part of the plant to another.

The needs of the growing parts are therefore not supplied when there is a deficiency in the soil, and these parts sicken and die.

The first thing to look for in diagnosing a deficiency, then, is the part of the plant that is affected. This will tell in which major group the deficiency belongs.

In the first group—symptoms primarily in the older parts of the plant—the effects can be subdivided into (1) those that are more or less general, and (2) those that are local.

General effects on the plant as a whole or on the older leaves are produced by nitrogen and phosphorus deficiencies. These two, then, make up subdivision (1). In both cases there is considerable dwarfing, and the leaves tend to assume an erect position, forming a rather acute angle with the stalk. In the case of nitrogen deficiency, the plant is abnormally light green, and more or less firing is evident on the lower leaves. In the case of phosphorus deficiency, the plant is abnormally dark green, there is little or no firing, and the leaves are unusually narrow in proportion to length.

Local effects on the older leaves are produced by magnesium, zinc and potassium deficiencies. These three make up subdivision (2). The local effects are loss of green color (chlorosis) and sometimes the development of areas of dead tissue (necrosis).

In the case of potassium deficiency, the chlorotic areas are yellowish and produce a mottled effect. They surround small dead spots or specks at the tips and margins of the leaves and between the veins. As the dead areas develop and dry up, they give the leaves a rusty appearance. Other parts of the plant are bluish green. An early symptom of potassium deficiency is a crimping under or cupping downward of the lower leaves at the tips and margins, and this becomes more pronounced as the deficiency becomes more acute.

In the case of magnesium deficiency, the pale areas are light green to almost white and occur between the principal veins, not primarily at the tips and margins. There is little or no spotting with dead tissue or cupping under of the tips and margins of leaves.

In the case of zinc deficiency, dead spots develop all over the leaf, not specifically at the tips and margins. Frequently they involve secondary and sometimes primary veins. The dead areas break down much more rapidly than in potassium deficiency.

So much for the first broad group.

The group characterized by effects on the young leaves or terminal growth can be classified in three subdivisions: (1) Chlorosis, or loss of color, in the young leaves without death of the terminal

bud, which indicates a deficiency of iron, sulfur or manganese; (2) death of the terminal bud preceded by loss of green color in the bud leaves, which indicates a deficiency of calcium or boron; (3) permanent wilting of the upper leaves, which indicates a deficiency of copper.

In subdivision (1)—chlorosis of the young leaves without dieback of the terminal bud—the veins tend to retain their green color if iron is the deficient element. The loss of color usually takes place only between the principal veins, although they too may be affected in extreme cases, when the entire leaf becomes white or yellow. Usually there are no dead spots.

If sulfur is the deficient element, the veins as well as the rest of the leaf tend to be light green—in fact, they may be even lighter than the rest of the leaf. There is not as great a loss of color as in the case of iron or manganese deficiencies, so that the leaves do not become white or yellow. There are no dead spots.

If manganese is the deficient element, the entire vein system of the leaf—even to the minutest branches—retains its green color in sharp contrast to the pale tissue between the veins. This gives the leaf a checkered appearance. Later, these leaves develop small dead spots scattered over the surface.

In subdivision (2)—death of the terminal bud—the young bud leaves first lose their green color and hook downward for about one-third of their length if calcium is the deficient element. Then the tips and margins of these leaves die, so that if growth occurs later they look scalloped and distorted. The plant is dark green.

If boron is the deficient element, the young bud leaves first lose their color at the base, which has a drawn appearance. The tip may remain green for some time. Usually the affected tissue rapidly breaks down, and if growth occurs later, before the leaf is too far gone, it has a distorted or twisted appearance. The color of the upper leaves of the plant is an unhealthy light green, and they roll downward in a semicircle from the tip toward the base. The principal veins and the midrib of affected leaves are extremely brittle, breaking readily when folded, and the tissue of the veins is discolored brown or black.

In subdivision (3), there is no typical chlorosis, and dieback of the terminal bud has not been observed. The dominant symptom of copper shortage is permanent wilting of the upper leaves.

The key which follows has been worked out for quickly identifying an unknown plant-food deficiency in tobacco.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS OF TOBACCO

A. Causal parasites or viruses present (not included in present discussions). *Parasitic and virus diseases*	
A. Causal parasites or viruses absent. More or less localized effects and decreased growth. *Commonly classed with nonparasitic diseases*	
B. Effects localized on older or lower leaves or more or less general on whole plant.	Element deficient
C. General on whole plant; also, yellowing and drying up or "firing" of lower leaves. Plant light or dark green.	
D. Plant light green. Lower leaves yellow, drying to a light-brown color. Stalk short and slender if element is limiting in later growth stages	Nitrogen
D. Plant dark green. Lower leaves may yellow and dry to a greenish-brown to black color; stalk short and slender if element is limiting in later growth stages	Phosphorus
C. Local, occurring as mottling or chlorosis with or without spots of dead tissue on lower leaves; little or no drying up of lower leaves.	
D. Lower leaves chlorotic and typically show no dead spots. Tips and margins turned or cupped upward. Stalks slender	Magnesium
D. Lower leaves mottled or chlorotic with small or large spots of dead tissue.	
E. Small spots of dead tissue between the veins at leaf tips and margins, which are tucked or cupped under. Stalks slender.	Potassium
E. Spots rapidly enlarge, involving in most cases the secondary and sometimes the primary veins. Leaves thick. Stalks with short internodes	Zinc
B. Effects localized on newer or bud leaves of plant.	
C. Terminal bud dies. Death is preceded by peculiar distortions at the tips or bases of young leaves making up the bud.	
D. Young leaves making up terminal bud first typically hooked, then die back at tips and margins so that later growth of such leaves produces a cut-out appearance at tips and margins. Stalk finally dies back at terminal bud	Calcium
D. Young leaves making up terminal bud first light green at base; then breakdown may take place at base of young leaf; if later growth follows, leaf shows twisted growth. Stalk finally dies back at terminal bud	Boron
C. Terminal bud remains alive; wilting or chlorosis of newer or bud leaves, with or without spots of dead tissue; veins light or dark green.	
D. Young leaves permanently wilted, no spotting or marked chlorosis. Stalks immediately below seed head unable to stand erect when shortage is acute at flowering stage	Copper
D. Young leaves not wilted, chlorotic with or without spots of dead tissue scattered over leaf.	
E. Young leaves chlorotic with spots of dead tissue scattered over leaf. Smallest veins tend to remain green, producing a checkered effect on leaf	Manganese
E. Young leaves chlorotic without dead spots. Chlorosis does or does not involve veins so as to make them dark or light green in color.	
F. Young leaves with veins of a light-green color or of same shade as tissue between veins	Sulfur
F. Young leaves chlorotic, principal veins typically green. Stalk short and slender	Iron

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Plate 1.—A tobacco plant grown under conditions of nitrogen shortage. Note the light-green color and the firing of the lower leaves.

Plate 2.—Symptoms of phosphorus deficiency in tobacco. Note the abnormally dark-green color and erect position of the leaves.

Plate 3.—A tobacco plant suffering from potassium hunger. Note the loss of color at tips and margins of leaves and the spots of dead tissue associated with cupping under of leaves.

Plate 4.—Potassium hunger in tobacco. Left, leaf from base of plant already has a ragged appearance. Center, leaf from higher up is less affected. Right, leaf from still nearer the top has just begun to be affected.

Plate 5.—Magnesium deficiency in tobacco. Four leaves, from the base of the plant upward (left to right), showing stages in loss of color. The lower leaves are the first to be affected.

Plate 6.—Magnesium deficiency (sand drown) in tobacco. Note the loss of color in the lower leaves, especially at tips and margins.

1 2

Plate 7.—Tobacco seedlings from plant bed. Plant 2, from untreated portion of seedbed, shows magnesium-deficiency symptoms. Plant 1 is normal 2 weeks after the soil was treated with 4 pounds of Epsom salts per 100 square yards. Compare the color and root development of the two plants.

1 2 3

Plate 8.—Tobacco leaves suffering from two mineral deficiencies: 1, Iron—note the loss of color except along the principal veins; 3, manganese—note the checkered appearance and associated dead spots. 2 is a leaf from a normal plant.

Plate 9.—Tobacco plant suffering from calcium shortage. The young leaves are distorted, while the older, lower leaves look normal.

Plate 10.—Boron shortage in tobacco. Note distorted upper leaves and dead terminal bud.

Plate 11.—Dwarfing, light-green color, and dead tissues due to manganese deficiency are shown in 2; 1 is a normal tobacco plant.

Plate 12.—Hands of cured tobacco, Maryland type. 1, from normal plants; 2, from plants suffering from manganese shortage—note the lack of desirable color and the spots.

A B

Plate 13.—A is a normal tobacco plant. B shows the reduced growth and crimping downward of leaves at tips characteristic of sulfur shortage.

Plate 14.—Iron chlorosis in tobacco. A is a normal plant. B was grown in a sand culture to which no iron was added; note loss of color in the upper leaves.

Plate 15.—Tobacco plants grown in sand culture, with zinc (A) and without zinc (B). Note the loss of color and the spotting of leaf tissues in B.

CHAPTER III

Deficiency Symptoms of Corn and Small Grains

By G. N. Hoffer and B. A. Krantz[1]

SOMEONE has said, "If starved plants could only squeal like hungry pigs, we would pay more attention to their fertilizer needs."

Fields of healthy, vigorous corn and of wheat or other small grains indicate high soil fertility. However, when the available supply of any one of the essential mineral elements becomes exhausted, growth is seriously impeded. The symptoms of a deficiency may be regarded as the "language" the plants use to indicate the nature of the distress affecting them (figure 1). In some ways these symptoms afford a better understanding of the nutrient relationships between soil and plant than can be obtained from detailed chemical analyses of the soil. Whenever possible, dominant symptoms of plant-nutrient deficiencies in corn and small grains should be translated into plans for corrective practices in the soil-management program.

It is difficult at times to interpret the visual symptoms of nutrient deficiencies in the field because so many environmental factors constantly affect the plant. Prolonged periods of adverse growing weather may harm corn plants. Severe winters may adversely affect winter grains. Insects and fungus diseases may make inroads on the crops and cause difficulties in the interpretation of deficiency symptoms. Diseases, insects and unfavorable weather are all likely to be most harmful to plants already weakened by malnutrition, complicating the symptoms in the field. For these reasons it is necessary to study typical deficiency symptoms in plants grown under controlled nutrient conditions.

The most common symptoms in corn and small grains at the present time are those caused by deficiencies in the supplies of nitrogen, phosphorus, potassium and magnesium. Deficiencies of calcium have recently been found in Illinois and Pennsylvania. Deficiencies of zinc and manganese occur in local areas.

[1] G. N. Hoffer is manager, Midwest office, American Potash Institute, Inc., and B. A. Krantz is research professor of agronomy, North Carolina Agricultural Experiment Station, and agent, Division of Soil Management and Irrigation, Bureau of Plant Industry, Soils and Agricultural Engineering, U. S. Department of Agriculture.

Nitrogen-deficiency symptoms are shown by corn plants in practically all parts of the country. Nitrogen is commonly deficient in most soils of the humid region, particularly in the South and the light-colored soils of the Midwest. Phosphorus, as well as nitrogen, is deficient in most unfertilized acid soils. In a few soils along the Atlantic seaboard, large amounts of phosphorus have accumulated from repeated heavy fertilization (8). Practically all muck and high-lime soils, and most sandy soils, are deficient in

Figure 1.—Learning the "language" of hungry corn plants is first aid in correcting your soil fertility problems.

potash. Potash is needed generally in the soils in the Southern States as well as in many soils in the Midwest that have been limed, treated with phosphate and planted to legumes. Besides these obvious examples, there are many soils of good original fertility which, through erosion, leaching, crop removal and mismanagement, are now coming to need replenishment of their plant nutrients.

On many farms the benefits from liming acid soils to obtain better responses to applied phosphates and to favor nitrification and the growth of legumes have been proved repeatedly. The value of manure is unquestioned. The maintenance of legumes in the rota-

tion is important. Even though legumes require mineral elements in large quantities, they serve as a connecting link between the vast reserves of free nitrogen in the air and the fixed nitrogen demanded by other crops in the rotation. They accomplish this best when properly inoculated and well fertilized. Plowed under, they enhance the aeration capacity of the soil and also supply organic matter with a high mineral content for the use of beneficial soil organisms and other crops in the rotation. The most efficient use of plant nutrients occurs under these improved soil conditions.

DIFFERENCES IN PLANTS AS INDICATORS OF PLANT-NUTRIENT DEFICIENCIES

Some crop plants are better indicators of plant-nutrient deficiencies than others. Corn plants with their wide expanse of broad leaves are better indicators of changes in the supplies of available plant nutrients than are the small-grain plants with their smaller and narrower leaves. Thus corn plants in rotation with other crops serve as excellent indicators of the fertility of the fields in which they are growing. This is especially true as to nitrogen and potash.

Though small grains in the rotation also may show signs of deficient soil fertility, their symptoms are, as a rule, less striking and more difficult to interpret than those of corn. Late frosts in the spring, prolonged wet periods and insect invasions often have damaging effects on the small-grain plants and make it difficult to diagnose the disturbance as definitely due to malnutrition. For these reasons the symptoms shown by corn plants will be discussed at length while those of the small grains will receive only general attention.

VALUE OF CHEMICAL TISSUE TESTS

It has been found by experience that the use of simple qualitative chemical tests for the presence of nitrates, inorganic phosphates and potassium salts in the tissues of corn and small-grain plants aids greatly in the field diagnosis of the symptoms induced by deficiencies of these plant nutrients. When well nourished and in good health, corn and small-grain plants carry reserves of these salts in their tissues during the active growing season, and the presence of such reserves is indicated by the tests. When the reserves of any of these nutrients become exhausted the tissue tests are negative and confirm the symptoms indicating deficiency.

These chemical tests are invaluable for use in the field when other complicating factors due to climate, disease or insects are involved. The tests can be used at any time during the growing season. Their use will be discussed in connection with the diagnosis of deficiency symptoms. The tests themselves and the preparation of the chemical reagents are described at the end of the chapter, page 86.

The best background for the diagnosis of deficiencies of the major nutrients is good field experience and the ability gained from it to evaluate all of the factors influencing the growth of corn plants. When this experience is supplemented with the information gained by making comparative chemical tissue tests on the highest yielding strains of corn plants and those growing under deficient nutrient conditions, a firmer basis is established for planning changes in the soil-management and fertilizer programs.

No attempt has been made to prepare a key for the classification of the symptoms of plant-nutrient deficiencies in corn and small grains based on external symptoms only, because of the difficulties of interpreting them without the supplementary use of the tissue tests. Sometime later it may become possible to reduce them to a key, when further research contributes new chemical tests for other plant nutrients.

DEFICIENCY SYMPTOMS IN CORN

The deficiency symptoms shown by corn plants are so striking that it is believed important to use them in determining plant-food needs not only for the corn crop but also for the other crops in the same rotation. It has been found that when the corn crop suffers from a lack of essential plant nutrients all of the other crops in the rotation will also respond to applications of the deficient nutrients.

Nitrogen

Nitrogen enters into the composition of many organic compounds in the plant. As an essential element in protein, it is needed for the growth and development of all of the living tissues. The corn plant uses more nitrogen than any other fertilizer element. It also has a higher nitrogen requirement than that of any other common nonleguminous crop. Nitrogen is needed by the corn plant throughout the growing season, but it is used in the greatest quantity during the grand period of growth which extends from about 2 weeks before to 3 weeks after tasseling. Sayre (33) found that the daily uptake was as high as 4 pounds during a part of the period and that

about one-half of the total nitrogen requirement was absorbed during this period. The nitrogen requirement for a 100-bushel corn crop varies greatly with the soil fertility and variety of corn used, but averages about 160 pounds per acre. The corn plant is very responsive to nitrogen variables, and fruiting does not appear to be disturbed by excessive applications, as in the case of a crop like tomatoes.

Nitrogen is necessary for early growth stimulation. This is especially important in cool springs and in regions with a relatively short growing season. Nitrogen deficiency in the young plant is characterized by a stunted and spindly growth and light yellowish-green foliage. The occurrence of this situation can generally be avoided by a liberal application of a high-nitrogen complete fertilizer at planting time. The omission of nitrogen from the fertilizer has been found greatly to retard early growth and even delay tassel emergence by as much as 10 days (23).

When nitrogen deficiency occurs later in the growth of the plant, especially during the grand period of growth, a rather definite leaf symptom develops. When the nitrogen-supplying power of the soil is below the daily nitrogen requirement of the plant, translocation of nitrogen will take place from the older to the younger tissue. The tips of the lower leaves are the first to show the loss of chlorophyll. This shows up as yellowing, since the yellow pigments in the leaf, such as the carotene and xanthophylls, predominate after the loss of the green chlorophyll pigment takes place (10). If the nitrogen deficiency persists, the yellowing will follow up the leaf midrib in the typical V-shaped pattern with the leaf margins remaining green as is shown in plate 1, left, and 9-B. Later the whole leaf turns yellow and the process proceeds up the plant leaf by leaf. Varying degrees of yellowing may be seen on as many as 3 to 4 leaves of a plant at one time. In some cases the yellowing may take place on the whole leaf and not show the typical V-shaped pattern. This is often found when the deficiency is accentuated by the occurrence of mild drought conditions. A few days after the leaf tissue yellows it dies, turns brown and dries up as is shown on the 3 lower leaves and the tip of the fourth leaf in plate 1, left, page 93. This dying of lower leaves is frequently referred to as "firing," and it may occur under either wet or dry conditions. A field view of this is shown on the right side of plate 2, page 93. Although nitrogen deficiency is by far the most common cause of firing, other conditions such as extremely dry and hot weather can also bring about the death of

leaf tissue. After the leaves are dead, it is sometimes difficult to diagnose the cause. An example of firing due to extremely dry, hot weather is shown in plate 1 (center). The important difference between this and nitrogen firing is that it occurred on the upper as well as the lower leaves of the plant. Usually the tip half of the leaf is affected more, although the whole leaf may dry up. The plants shown in plate 1 (center) were adequately fertilized.

Figure 2.—Soil moisture deficiency affects entire plants. The leaves curl upward, wilt and become very dry.

If the plants are observed during the development of the symptoms, it is easy to distinguish between nitrogen deficiency and dry weather effects. Plants which suffer from moisture deficiency wilt, and the leaves roll during the heat of day. This may take place for several weeks without any yellowing or firing if an adequate supply of nutrients was available before the dry period occurred, as is shown in figure 2.

If the soil supply of nitrogen is relatively low, a mild drought may greatly accentuate the nitrogen deficiency. Some of the reasons for this are: First, during dry spells when soil moisture moves upward, nitrates also move upward (24); second, as the topsoil dries out, it restricts the zone of major nutrient absorption, because plant roots cannot function in dry soil.

When visual leaf symptoms indicate a possible deficiency of nitrogen, a quick confirmation can be obtained by testing the plant tissue (figure 3) for the presence of nitrate as described at the end of this chapter, page 86, or by using Bray's new nitrate test powder (4) as shown in plate 19, page 105. This test powder is very reliable and eliminates the corrosive sulfuric-acid-diphenylamine test solution hazards. If visual nitrogen deficiency symptoms appear and there are no nitrates present, the deficiency is confirmed. However, in some cases the yellow leaf symptom has appeared when nitrates were found to be present. These observations appear to be contradictory, but further investigations have offered some clarification. In one case (25), a mild drought prior to testing had made

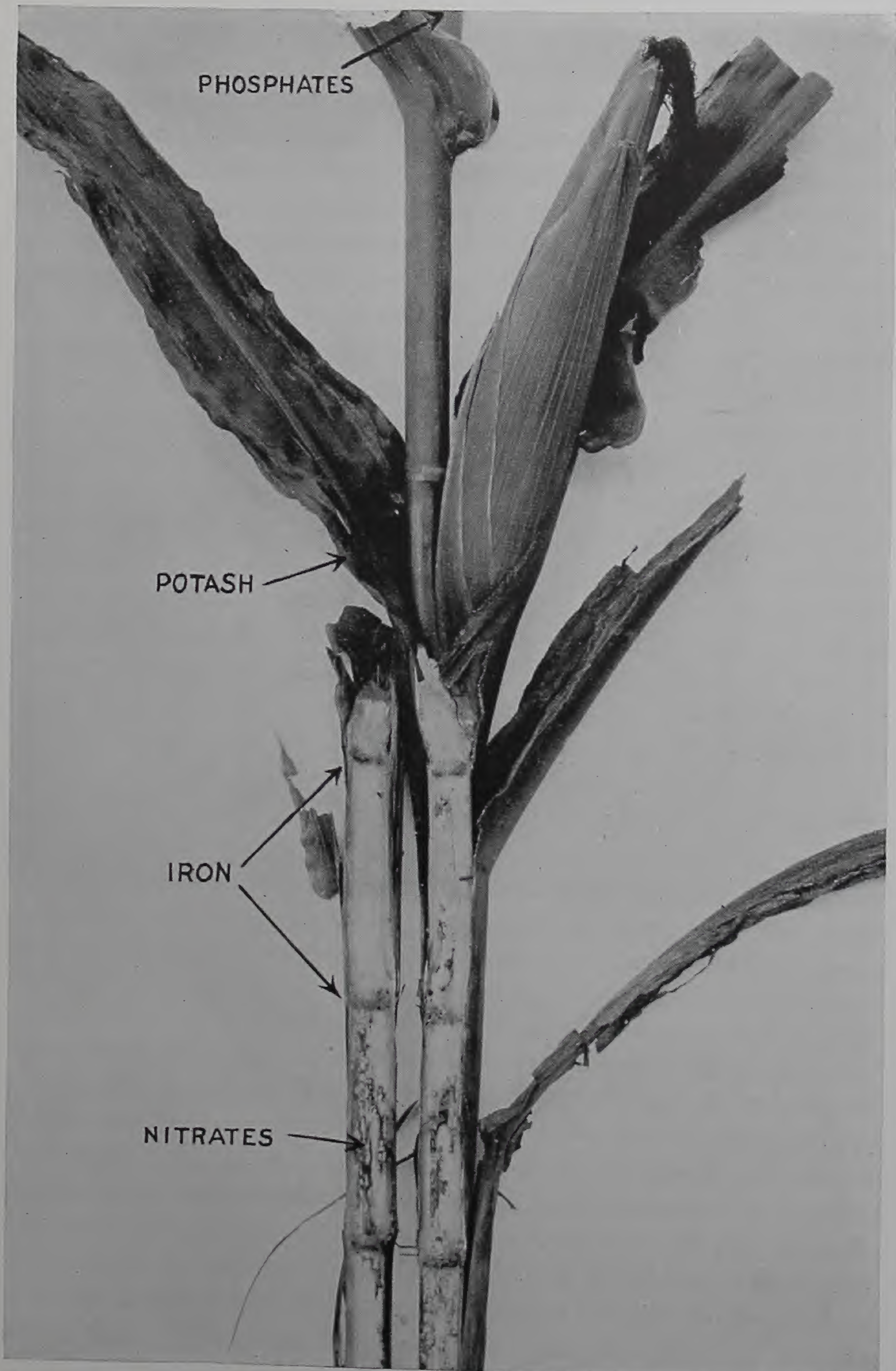

Figure 3.—When chemical tests are used to confirm nutrient-deficiency symptoms in the field, they are made on corn-plant tissues as indicated. Tests for potassium are made on the tissues in the base of the leaves; iron accumulations in the joint tissues indicate potassium starvation also. Tests for nitrates are made on the internodal tissues throughout the plant. Tests for phosphorus are made on stalk tissues just below the tassels.

some of the nitrogen unavailable and thus the visual nitrogen-deficiency symptoms developed. However, a rain had fallen 3 days before testing and had made nitrogen available, as was indicated by the test. Similar observations have been made in fields where late side dressings of nitrogen were applied. In another case (10), yellowish leaves were found to contain nitrates, but the phosphate level was so low that the plant was apparently unable to assimilate the nitrates. This is further described on page 68 under phosphorus deficiency. In cases of leaf-dying due to dry-weather injury, nitrates have also been found to be present in the plant. Thus the nitrate test is a valuable aid in diagnosing leaf symptoms of the corn plant.

Corn is one of the best indicator crops for nitrogen deficiency in any rotation. The use of legumes in a rotation is an excellent way to supply nitrogen for the corn crop. There is evidence, however, that supplemental nitrogen is usually needed, in addition to that furnished by the legume, to obtain maximum corn yields.

When young corn plants show visual nitrogen-deficiency symptoms, nitrogen fertilizers should be applied. Side-dressing with nitrogen is a commonly accepted practice in the Southeastern States. In North Carolina, for example, side-dressing with 60 to 100 pounds of available nitrogen at the knee-high stage is recommended for average conditions.

When nitrogen deficiency was observed at the early tasseling stage, substantial yield increases were obtained by immediate nitrogen side-dressing applications. However, the yield increase was much less than that obtained by applications at the knee-high stage (23).

Phosphorus

It is definitely known that all plant cells contain phosphorus compounds and that phosphorus is necessary for the cell division which results in the growth of the plants. Phosphorus is concentrated in the growing tissues in the tips of roots and shoots. It is found also in the developing kernels of grain, and when corn plants approaching maturity become starved for phosphorus, the developing seeds will accumulate this nutrient at the expense of all the mature tissues. Phosphorus is necessary, therefore, for the reproduction of these plants.

It is difficult to describe definite symptoms indicating phosphorus deficiency in corn. A retarded rate of growth and slow maturity of the plant are the chief symptoms, especially when other nutrients.

such as nitrogen and potassium, are shown to be available in sufficient quantities.

The retarded rate of growth is especially marked in the young seedling. In the Southeast early vegetative response to phosphorus fertilization is very common, even on soil with medium to high soil-phosphorus levels. This response may be apparent up through the silking stage, but final yield responses are found only on soils low in phosphorus (23). The foraging ability of the extensive fibrous

Figure 4.—Ears produced on slowly growing, phosphorus-deficient plants are often imperfectly pollinated because of the delayed emergence of the silks. Dropped rows of kernels result.

root system of corn and the fact that corn normally matures a month or two before the end of the growing season are given as possible reasons for the lack of final yield response.

The effect of phosphorus starvation in delaying maturity is particularly noticeable during the pollination stage. When the silks emerge slowly, defective types of ears are produced. Such ears are imperfectly pollinated and show rows of unfertilized seed rudiments. Figure 4 shows defective ears from plants starved for phosphorus during the later stages of growth. Note the irregularly formed rows of kernels.

Phosphorus deficiency in young corn plants is characterized by slow, stunted growth and dark-green color, and sometimes the leaves and stems have a tendency to become purplish. The purplish color

in plate 4, page 95, is due to the effect of accumulated sugars on the formation of the purple pigment, anthocyanin (10). The accumulation of sugars is due to phosphorus deficiency, but the color itself is dependent on the presence of the genetic factors for purple-pigment production in the particular strain of corn affected, as shown in plate 5, page 96. The plants were grown in controlled nutrient-solution cultures. Note that none of the plants of strain CC5 in plate 5 show any purpling of the leaves, even when they received only 5 parts of phosphorus per million of total solution. In plate 6, page 96, the plants of inbred Hy, also with 5 parts per million, are strongly purple. These differences in response are found to be common in other strains of corn and show that the purple coloring is limited to strains with the proper genetic constitution for its formation.

Unfavorable growing conditions such as a prolonged period of cool weather in the spring may cause a similar purpling in young plants. In this case it may be more or less temporary, but it has been reported frequently during cool weather in the northern parts of the Corn Belt.

Under conditions of severe phosphorus starvation the leaves of young corn plants may display symptoms very similar to those induced by nitrogen deficiencies (10), as in plate 3-C, page 94. Chemical tests of these tissues showed that they contained an abundance of nitrates. Phosphorus is necessary for the assimilation of the nitrates, and the plant tissues actually starve for nitrogen even though they contain the nitrate salts. The interrelation of these two plant nutrients is readily observed when tissue tests for both nitrates and phosphates are made on the plants. Thus a high nitrate and a negative phosphate test reflect a deficiency of available phosphorus even though the foliage symptoms indicate nitrogen hunger. Tissue tests often relieve the confusion resulting from interpreting symptoms solely on the basis of foliage characteristics.

Because of such uncertainties, symptoms of phosphorus hunger in corn plants should be confirmed by chemical tests on the plant tissues for the presence or absence of reserve quantities of inorganic phosphates, plate 17, page 104. Corn plants utilize these phosphates rapidly, and in vigorously growing plants only small reserves may be found. The avidity with which young corn and small-grain plants draw upon the supply of phosphates in the soil for their early growth and establishment of their root systems makes it imperative that an abundant supply be available. It explains the almost unfailing early response of these crops to phosphatic fertilizer properly applied.

Since inorganic phosphates are combined very rapidly into organic compounds in corn plants, and these are utilized to build up new plant parts and finally the mature grain, a reserve supply of inorganic phosphates in the plants is necessary throughout the growing season. Whether a reserve is present at any particular time can be detected readily by relatively simple chemical tests (37) in the cornfield, as described on page 86.

The tissue tests can be made on plants at any stage of growth and much practical information on the relative availability of phosphates in different soils can be gained from them. They serve to check on the effectiveness of applied phosphatic fertilizers. Very often the amounts of phosphates supplied are insufficient for the best growth and maturing of the corn crop.

The relative effectiveness of using phosphates in the row compared with broadcasting and plowing under can also be shown by testing the plants during the growing season. In such studies the chief differences in the appearance of the plants may be in their size. Small plants may appear healthy otherwise, but the more rapid, sturdier growth of other plants in the same field may be explained by the larger quantities of inorganic phosphates found in their tissues.

On soils alkaline in reaction, however, poor growth may be due not to lack of phosphorus but to a deficiency of one or more of the so-called minor or trace elements; manganese and boron are sometimes needed to balance the plant-nutrient supply and enable the plants to grow normally. In acid soils the phosphates may be fixed in combinations with iron and aluminum. Chemical tests on the tissues tell at once whether phosphates have been absorbed.

Potassium

Investigations show that potassium is intimately related to the production of sugars, starches, cellulose and proteins in plants, yet, so far as is known, it does not enter permanently into the composition of any of these organic compounds. It is needed in all processes of growth of the plant cells and also influences their rate of respiration. Potassium helps to protect plants from excessive losses of water during periods of drought, and it lessens the injuries due to low temperatures. Potassium salts move readily from one part of the plant to another, and because of this mobility the symptoms of potassium hunger appear first in the oldest leaves. The younger parts of the plant draw the potassium away from these older parts (20).

Potassium salts are needed in abundance for the normal growth and development of the corn plant from the time the seed germinates until the plant is matured and the next generation is provided for in the new set of seeds. Healthy, vigorous corn plants always contain large amounts of potassium salts in their tissues, whether in the seedling stage or in plants approaching maturity.

Eckstein, Bruno and Turrentine (11) have described the symptoms of potash deficiencies of practically all commercially important crops.

The supply of available potash in the soil may become acutely deficient at any stage of growth of the corn plant. The signs of hunger may appear in the seedlings or young plants, or they may not become apparent until the plants are approaching maturity. The symptoms will be described as they appear at different stages of growth of the plants.

In Young Plants

The first symptom of potassium deficiency is a diminution in the rate of growth of the seedlings and young plants. Soon definite leaf characteristics develop, pointing to potassium deficiency. The young leaves are yellowish green to yellow in color, or sometimes only streaked with yellow. The edges and tips become dry and appear scorched or fired. These early symptoms are shown in plates 1 (right) and 7, pages 93, 97. When the deficiency of available potash is less acute, though growth is retarded, the leaf symptoms may not appear until the plants are further developed.

When the foliage symptoms of potassium deficiency are recognized early in the growth of corn plants, it is possible and profitable to apply muriate of potash in the row or hill and correct the deficiency. The application should be made prior to the last cultivation, and it is suggested that 150 to 200 pounds of muriate of potash per acre be used. In 15 experiments in Iowa on high-lime soils, an average increase of 12.8 bushels was obtained by side-dressing the young corn plants with muriate of potash at the rate of 200 pounds per acre. In southern Illinois, during the same season, an average increase of 8.2 bushels was obtained in three tests on acid, poorly drained soils (15). Since then many profitable responses have been obtained by similar treatments (22).

In Older Plants

As the plants increase in size, the need for potassium increases; and if the supply becomes inadequate, foliage symptoms similar to

those found in younger plants appear. The leaves are streaked with yellow or yellowish green, and the edges are dry and scorched. This marginal scorch (plates 7 and 10, pages 97, 99) is the outstanding leaf symptom. In severe cases the leaves become badly damaged and the growth of the plants is dwarfed because the tissues between the nodes do not develop fully. In the plant in plate 10, all of the leaves show the marginal firing. The plant is weak. Only small areas of the leaves remain green and in condition to manufacture carbohydrate foods for the developing ears. If these plants produce ears, they are usually chaffy nubbins of low feed value. The tip ends of the ears are unfilled; the kernels that do form are poorly matured and starchy, and they easily become infected

Figure 5.—A, Ears on plants receiving complete fertilizer. B, Potassium-starved ears from plants receiving nitrogen and phosphorus only are of low feed quality.

Figure 6.—Nitrogen-hungry plants grow spindling and tall. Potassium-starved plants have relatively short internodes and are dwarfed. The leaves appear too long for the height of the plant.

with ear-rot organisms, which often affect germination detrimentally. Ears from potassium-starved plants are shown in figure 5.

Figure 6 shows the characteristic differences between nitrogen and potassium-starved corn plants. Nitrogen-starved plants grow spindling and the leaves are yellowish green to yellowish orange in color. The oldest leaves become dry and appear fired as shown in plates 7, 9-C, and 10, pages 97, 98, 99. The potassium-starved plants are dwarfed in size, the leaves appear to be too long for the stalks, and they are affected by the typical marginal scorch. Such plants become weak and lodge badly because of defective root systems.

Hoffer (19) has shown that iron compounds accumulate in the tissues of the joints of corn plants when the supply of available soil potash is deficient. The iron accumulations are seen when the plants are split open lengthwise and an acidulated solution of potassium thiocyanate (see page 89) is applied to the exposed joint tissues. The amount of iron accumulated at the stalk nodes is determined by the amount of potassium salts in the plant sap (figure 3). When potassium is entirely lacking, the purplish-red color is intense. These iron accumulations disrupt the translocation of foods from the leaves to the roots, and the latter are starved and weakened. They then become predisposed to injuries by many of the fungi or molds inhabiting soils in which corn has been grown for some time. When the roots become sufficiently rotted the weakened plants may lodge so badly that they lie flat on the ground. Lodging of corn plants, as shown in figure 7, is an important symptom indicating a deficiency of available potash in the soil. Heavy accumulations of iron compounds in the joint tissues confirm the symptom.

Healthy, vigorous plants always contain potassium salts in the leaves and stalk tissues in quantities that can be detected by simple chemical tests adapted for use in the field (page 87). A negative test indicates a definite deficiency even before the appearance of the foliage symptoms. Many investigators have found that the content of potassium in the sap of the corn plant reflects the relative availability of this element in the soil. Tests are often needed to distinguish potassium-deficiency symptoms from those induced by bacterial wilt (Stewart's disease) and the leaf disease caused by *Helminthosporium* species. If reserve potassium is present in diseased plants showing symptoms resembling potassium starvation, it eliminates a deficiency of potassium as a contributing factor.

The recognition of symptoms of potassium deficiency late in the development of the plant is important even though nothing can be

done to benefit the current crop. The symptoms are useful in formulating plans for the management of these fields in the future.

It is true that potassium becomes available slowly in many soils, but researches in Illinois (3) show that there is no way of increasing the rate of liberation of potassium in depleted soils enough to meet the requirements of the corn crop satisfactorily. It has been proved also that when the corn crop suffers from a lack of enough available potassium for normal growth and production, all of the other crops

Figure 7.—Plants in foreground are starved for potassium. Weak stalks result when the available potassium in the soil becomes depleted by crop removals in a rotation following limestone and phosphorus fertilization.

in the same rotation will also respond to potash fertilization. In many fields where limestone and phosphate have been used for growing legumes in the rotation with corn, potash deficiencies are appearing because of the large quantities of potassium removed in the increased hay and grain yields.

Magnesium

Magnesium is a component of the chlorophyll molecule, the green pigment in all plants. The salts of magnesium are mobile and distributed throughout the entire plant. The younger parts of the plant may draw on the older parts for magnesium when the soil supply becomes low, and this relation helps to explain the type of symptoms that result.

The symptoms in corn are definite and easily recognized. When the supply of magnesium becomes deficient, the chlorophyll in the

oldest leaves reflects the trouble first. Here a slight yellow streaking develops between the parallel veins in the leaves. With the continued migration of magnesium from the older leaves to the younger parts of the plant, there is a definite and sharply defined series of yellowish-green, light-yellow, or even white streaks extending the entire length of the leaves. With an acute deficiency, these streaked tissues may dry up and die, and all of the leaves ultimately may show the streaking. Plate 8, page 97, shows these symptoms as they appear in a mature plant.

Magnesium deficiency in corn has been reported from various parts of the Southern States and has also been found in Massachusetts (21). In some cases the deficiency is believed to be intensified by the unbalanced plant-nutrient conditions resulting from the continued use of sodium salts in fertilizing other crops in the corn rotation (5).

Magnesium-deficiency symptoms may become prevalent in parts of the Corn Belt and should be watched for in the more acid, unlimed soils (or soils on which *calcitic* limestone was used). Usually, however, nitrogen and phosphorus deficiencies occur in these acid soils, and until they are corrected the magnesium deficiency may not become dominant. The use of dolomitic limestones for other crops in the rotation has no doubt delayed the appearance of magnesium-deficiency symptoms in corn plants in many localities.

Calcium

Calcium is essential for the growth and development of corn plants. Some of it becomes permanently fixed in various tissues of the plants. The leaves contain the largest quantities, less is found in the stems and roots, and the least amounts are in the grain and cob. Numerous roles have been ascribed to calcium, although some are little understood. Calcium influences the translocation of foods manufactured in the plants and the physiological availability of other nutrient elements, and it acts as a neutralizing agent preventing the accumulation of toxic materials in plant tissues.

The corn crop grows mostly on soils that are only slightly acid or that have been limed for other crops in the rotation, and consequently it has suffered little if any from a deficiency of calcium. No definite symptoms of calcium deficiencies have been described in corn growing in the field.

DeTurk[2] has produced calcium-deficiency symptoms in corn plants

[2] Private correspondence with the senior author.

Courtesy of E. E. DeTurk, University of Illinois

Figure 8.—Calcium hunger. Yellow dent corn, inbred Tr, has a high calcium requirement. With 10 and 25 parts of calcium per million, each plant shows the tip ends of the leaves gummed together. With 50 parts of calcium per million the plants appear normal.

Courtesy of E. E. DeTurk, University of Illinois

Figure 9.—Calcium hunger. The open-pollinated strain of Reid yellow dent corn used in this experiment has a low calcium requirement. Plants grow well with 10 and 25 parts of calcium per million. Compare these plants with those in figure 8.

growing in controlled nutrient cultures. Young plants show very distinct symptoms. The tips of the unfolding leaves gelatinize, and when dry they stick together. As the plant continues to grow, the tip ends of the leaves form the pattern shown in plate 3-B.

In these investigations DeTurk has shown also that some strains of corn can tolerate a deficiency of available calcium better than others. Figures 8 and 9 show the difference between an inbred strain of yellow dent corn and an open-pollinated yellow variety. Fifty parts per million of calcium were necessary for the inbred strain to grow normally, while only 10 parts were needed by the open-pollinated variety. These physiological differences in response may help to explain the wide variations in adaptation that some strains of corn possess, particularly in open-pollinated varieties.

Boron

Boron salts are readily fixed in plants, and they are relatively immobile in comparison with salts of potassium, magnesium and phosphorus. A continuous supply during the growth of the plants is necessary. Boron is required in small amounts by most plants and has a place in the fertilization of fruit, truck and field crops that is becoming increasingly important. The demands of the corn crop and of cereals in general seem to be lower than those of such crops as the legumes, tomatoes and sugar beets in the same rotation with them.

Nusbaum (28) found boron-deficiency symptoms in both sweet and field corn in a preliminary field experiment on an infertile, deep-phase Norfolk sandy-loam soil with a pH of 5.2. This is the only report which has been found of boron-deficiency symptoms on corn growing under field conditions. It was observed that the plants in the no-borax plots were yellowish in color, had weaker ear shanks and stalks, and averaged about one foot shorter than the plants in the plots treated with 5 or 10 pounds of borax per acre. The total number of ears was increased about 26 percent, but the number of prime ears was doubled, by borax treatment. He also observed that some of the ears in the no-borax plots showed unilateral or one-sided shriveling on the side of the ear which faced the stalk, as is shown in figure 10. This symptom was not observed in the borax-treated plants.

The field corn reacted much like the sweet corn, but the deficiency symptoms were not quite as marked. The yields with 4, 5, 10, 20 and 30 pounds of borax were 36, 48, 48, 26 and 29 bushels per acre, respectively. All plots received 600 pounds per acre of 4-10-6 at planting and 200 pounds of ammonium nitrate as side dressing.

Pettinger, Henderson and Wingard (30) attribute a type of sterility in corn to boron starvation. Sand cultures were used in their experiments.

Courtesy of South Carolina Agricultural Experiment Station

Figure 10.—Left to right: Ear from healthy boron-treated corn plant, and three ears from boron-deficient plants. Note one-sided shriveling of kernels on the three ears from the no-borax plot.

Eltinge (12) describes the effect of boron deficiency on the corn plant as causing a thickening and brittleness of the roots. The leaves of the young plants do not unroll and the leaf tissues break down.

Ferguson and Wright (14), working with sand cultures, found that a deficiency of boron caused no external symptoms on Golden Bantam sweet-corn plants, but the ears showed a marked corky brown band extending along the outer edge of the cobs at the base of the kernels. Cobs of plants supplied with boron had a clean, healthy, greenish-white color.

J. W. Shive, of the New Jersey Agricultural Experiment Station, has kindly submitted a photograph of corn leaves (figure 11) taken

from boron-starved plants grown in pot-culture tests conducted by him. A normal leaf (A) is compared with the boron-deficient leaf (C), showing wide white stripes between the veins. These stripes are formed by the coalescence of small, white elongated spots between the veins. The younger leaves on these plants are dwarfed, and when the older leaves are stripped back the tissues of these younger leaves are seen to be white and the growing tips dead. When the amount of boron exceeded the normal requirement of the corn

Courtesy of J. W. Shive, New Jersey Agricultural Experiment Station

Figure 11.—Corn leaves. A, Normal leaf. B, Boron-starved plant; youngest leaves and tip of shoot dying. C, Older leaves develop yellowish-white stripes. D, Boron toxicity causes an edge "scorch," very similar in appearance to a symptom of potassium starvation.

plant, toxicity resulted and the symptoms produced were very similar to those induced by potash deficiency. This was also observed by Nusbaum (28) in sweet corn. The edges of the leaves (figure 11-D) became brown and appeared scorched.

Zinc

"White bud" of corn plants is a type of chlorosis frequently found in fields in constant cultivation in central, north and northwest Florida. Zinc sulfate applied to corn in these acid mineral soils will correct the chlorosis and give increased yields of corn. Barnette, Camp, Warner and Gall (2) described the symptoms shown by seedlings as follows:

In affected soil areas symptoms of white bud begin to appear

within a week or two after the emergence of the corn seedlings. The full development of the chlorophyll in the older leaves of the seedlings scarcely takes place before light yellow streaks appear between the veins. Small white spots of inactive or dead tissue develop rapidly in the leaves, while some small white areas that never have chlorophyll are present. The unfolding buds have leaves that are white to light yellow in color. This latter characteristic has given rise to the use of the term "white bud" by farmers. Zinc deficiency has also been reported in Alabama by Wear.

Plate 3-A shows a zinc-starved corn plant. The lower leaves have died and the upper leaves show yellow striping between the veins, while the inner, youngest leaves are practically white. The internodes of the plant are definitely shortened and the growth is stunted.

No reports of zinc deficiencies in the Corn Belt States have been noted to date.

DEFICIENCY SYMPTOMS IN SMALL GRAINS (WHEAT, OATS, BARLEY, RYE)

The common symptoms induced by deficiencies of nitrogen, phosphorus and potassium in wheat, oats, barley and rye are in many respects similar for all these crops. For two reasons the symptoms displayed by young plants only will be described: (1) Unless the symptoms are recognized before the plants are 6 to 8 inches in height, no remedial practices can be used that will benefit the immediate crop; and (2) the symptoms shown by older plants when heading out or later are often so complicated by diseases and other factors that it is difficult to attribute them definitely to malnutrition.

Figure 12 shows oat plants growing in pot cultures. The plants in the pot on the right which were given complete fertilizer (nitrogen, phosphoric acid, potash) serve as a check for comparison with those in the other pots in which one plant nutrient was omitted.

In the field the most readily identified symptoms are those resulting in differences in the color and height of the plants, their stooling ability, and the strength of the stalks.

The principal value of determining the causes of deficiency symptoms in the small grains is the information gained for correcting the soil-management program for all crops in the rotation with these small grains. It is important that symptoms be diagnosed carefully before any remedial measures are considered.

Courtesy of Purdue University Agricultural Experiment Station

Figure 12.—Oats in Crosby silt loam of low fertility. Pot 16 (NPK), treated with complete fertilizer, serves as check; plants healthy and vigorous. Pot 13 (PK), nitrogen starvation; plants spindling, yellowish green; slightly purplish stems. Pot 14 (NK), phosphorus starvation; plants dark green; stems weak, slightly purplish tinged. Pot 15 (NP), potassium deficiency; dark-green, weak plants, with oldest leaves brown and tip ends deadened.

At best the leaf symptoms displayed can be interpreted only with difficulty, because there are so many factors to complicate them. Valuable help is obtained in determining the nutrient needs of these crops by making comparative tissue tests for nitrates, inorganic phosphates and potassium on healthy plants of high-yielding varieties and those showing defective growth in different fields or even in the same field (page 88). The comparative tests will invariably give the clue to the nutrient deficiency. It is particularly instructive to determine the causes of different kinds of lodging induced by deficient or unbalanced supplies of nutrients; to check on the relation of available phosphates to stooling; to study the nitrogen-potassium relations to the incidence of rusts, mildews and other diseases. Field chemical tests are also useful at times in interpreting a lack of response of these crops to fertilizers improperly applied.

Nitrogen

The plants in the PK pot in figure 12 are deficient in nitrogen. They are erect and spindling, the leaves are yellowish green to yellow, and the stems are purplish green.

Plate 12, page 101, shows a field view of nitrogen-deficient oats. Plate 11-A, page 100, shows a nitrogen-starved leaf from an oat

plant; it is yellow and the tissues are drying out from the tip toward the base. This leaf symptom is the same for wheat (plate 3-D, page 94) and for barley and rye.

Cool, wet weather during the early spring inhibits the formation of available nitrogen in the soil. Often plowing under corn and other crop residues results in starving the newly seeded oats or barley for nitrogen, because the bacteria active in the decomposition of the organic matter use what little nitrogen is available in the soil and none is left for the new plants until nitrification becomes active in warm weather. When the previous corn crop has been amply supplied with nitrates, a "row effect" is often seen in small-grain fields.

Another common demonstration of nitrogen deficiency occurs when small grains are seeded in fields that were in pasture the preceding season. Dark-green patches of vigorously growing plants are found on spots that had been fertilized by droppings. These "Juno spots" demonstrate a general lack of fertility in the rest of the field and show the value of manure as a fertilizer.

Although the symptoms of nitrogen deficiency are rather specific in young small-grain plants, there are times when it may be desirable to confirm them by the use of chemical tissue tests prior to using top dressings, as described on page 88.

Phosphorus

Small-grain plants require large quantities of phosphorus for the production of the seed and are dependent upon available phosphates for stooling. The interpretation of phosphorus-deficiency symptoms in the field is difficult because there are no outstanding specific external symptoms that point directly to phosphorus hunger. Slow growth and lack of stooling are the common signs of phosphorus deficiency, particularly when the plants are dark green and apparently healthy otherwise.

The dwarfing effects of phosphorus deficiency on the oat plants in the pot without phosphorus are shown in figure 12. The leaves of the plants were dark green. Sometimes the leaves of small-grain plants also show a purplish tinge. The right side of figure 13 shows a typical example of the retarded growth in wheat due to phosphorus deficiency. The unphosphated plants on the left headed and matured about one week later than the phosphated plants. The

yield was increased 7 bushels per acre by this phosphate application.

Plate 14-C, page 102, shows the effects of phosphorus starvation on a wheat leaf. The tips of the older leaves die, and this dying of the tissues proceeds toward the base. This symptom so closely resembles the firing of nitrogen-starved (B) and potassium-starved (D) leaves that it is difficult to use it for diagnostic purposes in the field. Indeed, other factors may induce similar effects to complicate matters. Plate 11-B shows oat leaves starved for phosphorus. The firing is very similar to that of the wheat in plate 14-C.

Courtesy of W. H. Rankin, North Carolina State College

Figure 13.—Wheat plants need abundant phosphate to respond to extra applications of nitrogen. Note stunted plants in plot to right which received no fertilizer phosphate.

Small-grain plants growing vigorously contain reserves of inorganic phosphates in their tissues until the grain is formed. Any uncertainty regarding a deficiency may be cleared up quickly by making chemical tests for inorganic phosphates in the stem tissues of these plants. Of course the conclusion to be drawn from negative tests is that more available phosphates must be used in the fertilizer program for these crops.

Potassium

The importance of potassium in small-grain plant economy is high although the quantities demanded are less than for corn and legume crops.

There is one common symptom of potassium deficiency that is found in small-grain plants and other grasses—the edge scorch of the leaves. In early stages the tips and margins of the older leaves

Figure 14.—Wheat. Plants at left received 150 pounds of 0-20-10 fertilizer; those at right, 150 pounds 20-percent superphosphate only. Potassium strengthens the straw and prevents lodging. This demonstration was in a field where the available potassium had become depleted by crop removals following liming and the continued use of phosphates only.

turn yellow, then brown, and finally die, producing the scorch symptom. Later the stalks become weak and the plants show the weaknesses noted in the pots without potash in figure 12.

Plate 14-D shows a wheat leaf from a potassium-starved plant. The edge of the leaf shows the characteristic marginal scorch. The leaf is dying from the tip end.

The foliage symptoms shown in plate 14 for nitrogen, phosphorus and potassium deficiencies, while definite when obtained under controlled nutrient conditions, are relatively unsuitable for field diagnosis. Unless the leaf symptoms are confirmed by chemical tissue tests (page 88) it is practically impossible to guess their significance and use them to determine the fertilizer needs of these crops. Tissue tests for potassium are very reliable.

In barley, a deficiency of potassium results in the formation of small purplish-brown spots on leaves showing the marginal-scorch symptom. Plate 11-D shows this typical symptom of potassium deficiency. The cause of the spotting is unknown. The spots do not develop on the leaves of plants grown with adequate potash fertilization.

A deficiency of potassium results in weak stem development in small-grain plants approaching maturity. Figure 14 shows the weakness of wheat stems low in potassium. Both plots had received phosphate, and the plot to the left had received muriate of potash in addition.

Figure 15.—Oats. Aroostook County, Maine. Rows at right were magnesium-starved; plants yellow and stunted. Rows at left received a spring application of magnesium sulfate at the rate of 50 pounds per acre; plants growing normally and heading out.

The shriveling of grain may be caused by potash deficiency as well as by many conditions of nutritional unbalance. Since the shriveling is also induced by rusts and other disease factors, the causes of defective grains must be traced throughout the growing season.

Magnesium

Little attention has been given to the symptoms induced by magnesium starvation on small-grain plants in this country. Most of the investigations have been made on corn and the larger-leaved crops. Chucka and Lovejoy (6) report increased yields of wheat, oats, barley and rye from magnesium fertilizers. M. H. Lockwood, in private correspondence with the senior author, supplied evidence of the response of oats to a spring application of magnesium sulfate (figure 15). The magnesium-deficient plants were dwarfed and yellow. Thornton, at the Purdue Agricultural Experiment Station, produced symptoms of magnesium starvation in wheat in controlled nutrient cultures (data unpublished). The plants were stunted in growth, and the leaves showed a distinct mottling of

lighter yellowish-green patches in contrast to the normal green of the magnesium-fertilized plants. Plate 11-C shows this symptom. Plate 13 shows magnesium-deficiency symptoms in oats.

At best these symptoms would be diagnosed with difficulty in the field. It is quite likely that magnesium deficiencies will be detected first in the larger-leaved crops in the rotation with small grains, and that the latter will benefit from the remedial measures for these other crops.

Boron

No reports have been noted of any symptoms attributed to boron deficiencies in fields of small grains in this country. Purvis (32) states that grasses and cereals apparently require very little boron.

Manganese

Manganese is an essential element for plant growth. Its role in plants presumably is that of a catalyst, although this is not definitely proved. Most investigations have been made on this element in relation to its influence on the chemical and biological reactions in the soil. The processes of nitrogen fixation and ammonification in the soil are dependent upon its presence. Manganese deficiencies are found mostly in soils high in calcium carbonate.

Albert (1) has reported on manganese deficiency in oats in South Carolina. Oats growing in the heavily limed fertility plots at the Pee Dee Experiment Station displayed a bright yellow color of the leaves, with the leaves breaking down at their basal ends and dying slowly. The tip ends remained yellowish green and alive. These symptoms, according to Albert, are corrected by applications of 100 pounds of manganese sulfate per acre.

The "grey-speck disease" of oats, described by Davies and Jones (9) in Wales, has also been reported by Cook and Millar in Michigan (7).

Copper

Copper as an essential element for plant growth was proved by Sommer (34), and Harris (17) has recently demonstrated the control of a nutritional disorder of oats in Florida by the use of copper salts.

No other reports on the use of copper on small grains have been noted.

CHEMICAL TISSUE TESTS

Tests for Corn

Nitrates

Cut out a small section of the stalk or slice a portion of a leaf into small bits. Place these pieces in a glass vial or on a clean porcelain plate and apply a few drops of concentrated sulfuric acid containing 1 percent of diphenylamine. The older corn stalks in the field may be cut lengthwise and the freshly exposed tissues tested for nitrates by applying a few drops of the test solution. The distribution of nitrates in the plant can be noted by testing the tissues of the stalk from the base to the top.

If nitrates are present in the tissue, a blue color is produced immediately. This positive result is typical of all dark-green corn plants. If no blue color is produced, no reserve nitrates are present and the evidence confirms the yellowish-green symptom indicating nitrogen deficiency.

Another useful test for nitrates is made with the Bray Nitrate Test Powder as described in Selected Reference 4. The test is illustrated in plate 19, page 105.

Phosphates

Whenever possible, always make comparative tests of plant tissues from similar parts of phosphorus-starved plants and those growing normally in the same field.

It is suggested that tissues be taken from parts of the plants as follows:

Young plants—base of stalk.

Plants in tassel—tissue of stem below tassel.

Ear stage of development—compare tests of kernel tissues versus stem tissues of same plant.

Place a volume equivalent to a level teaspoonful of finely cut plant tissue in a glass vial, add 10 cc. of the phosphate-test solution (described later) and shake vigorously for 1 minute.

Then add the phosphate-test powder (also described later), in volume equal to a mustard seed, to the solution and shake thoroughly.

Refer to plate 15, page 103, the phosphate color chart, for interpretation of tests:

(A) A dark-blue solution indicates an abundant supply of inorganic phosphates in the plants at the time the test is made, as shown in plate 17, page 104. Note test of plant fertilized with phosphate (left).

(B) A medium-dark blue indicates an adequate supply for the present stage of growth of the plants.

(C) A light-blue, greenish or yellowish-green color indicates an inadequate supply of phosphates for normal growth and development of the plants, as shown in plate 17. Note the absence of blue color in the test solution at right.

Ample reserves of inorganic phosphates are associated with health and vigor of corn plants. The reserves may be high in plants deficient in nitrogen or potassium or both. It is important always to ascertain the relation to these other plant foods, reserves of which also are necessary for healthy growth.

Only when all three of these plant nutrients are found in reserve quantities should the dark-blue phosphate test be interpreted as indicating a satisfactory supply of available phosphates in the soil.

A negative test for phosphate indicates an inadequate supply of available phosphate in the soil. Tests for nitrates and potassium salts are important to complete the diagnosis and may help the interpretation of combined symptoms of nitrogen and phosphate hunger frequently found in plants in many acid soils. A negative potassium test on these phosphorus-deficient tissues indicates a deficient supply of this plant nutrient also.

Potassium

Two test reagents are required to detect the presence of potassium in corn-plant tissues. Their preparation is described on page 89. Reagent No. 1 consists of a solution of sodium cobaltinitrite and sodium nitrite in distilled water acidulated with acetic acid. Reagent No. 2 is 95-percent ethyl alcohol.

Whenever possible always make comparative tests of tissues selected from similar parts of plants that appear healthy and plants showing symptoms that indicate potassium hunger. If the tests are negative for the plant showing the symptoms while the healthy plant tissues contain potassium, the diagnosis of potassium deficiency is confirmed.

The following tissues are suggested for the tests:

Young plants—tissues from the lower part of the stalks.

Older plants—internodal stalk tissues or the basal portions of the leaves at the nodes bearing the developing ears.

After selecting the tissues to be tested, cut the material into small bits, place one-half teaspoonful in a glass vial, and add 10 cc. of Reagent No. 1. Shake vigorously for 1 minute. Then add carefully 5 cc. of Reagent No. 2 and mix thoroughly. Let the vial stand approximately 3 minutes and note the turbidity, if any, that develops.

Refer to plate 16, page 103, and compare the density of the cloudiness (turbidity) of the solution with the potassium-test chart.

(A) Clear solution. If the solution remains clear, as in plate 18, right, page 104, there were no potassium salts in the tissue tested. A negative test of this kind confirms the diagnosis of potassium-hunger symptoms.

(B) Turbid solution. If the solution shows turbidity, as at the left in plate 18, its relative density may be approximated by noting whether the heavy black lines of the chart can be seen through the solution. Any turbidity whatever indicates the presence of potassium salts in the tissues, and the denser the turbidity, the higher is the potassium content. When the solution carries a dense precipitate, the plant was well supplied with potassium up to the time the test was made.

Any symptoms displayed by such plants are due to factors other than potassium starvation. No response to additional potash applied to the soil can be expected until the limiting factors are corrected.

If the solution carries only a slight turbidity, particularly when the tissues from young plants are tested, the soil supply of available potash may be just

sufficient to meet the immediate needs of the plant. It may become deficient later when most needed to produce good yields of well-matured corn.

Tests for Small Grains

Nitrates

The diphenylamine test solution and Bray's Nitrate Test Powder are used in the same manner as recommended for corn tissues. By cutting several plants lengthwise, or by cutting several leaves into small pieces and applying several drops of this test reagent, the presence of nitrates may be detected readily if a blue color develops. If none appears, the absence of reserve nitrates is indicated, and the yellowish-green symptom of nitrogen hunger (plate 12, page 101) is confirmed. Improvements in soil conditions favoring nitrification may change the nitrogen relations in a few days. These nitrate tests reveal such changes. In older plants the nitrate tests are useful up to the time the heads develop.

Phosphates

The same test reagents and procedure are used as described for corn tissues. Use leaf tissues of young plants and stem tissues of older plants for the tests. Refer to plate 15, and check the test results.

A positive test for phosphate in small-grain plants shows that the soil supply of available phosphates was sufficient for the plants at the time of making the tests, and that any symptoms shown by the plants are caused by factors other than phosphorus hunger.

A negative test shows that the available phosphate supply is inadequate and is the limiting factor or one of the limiting factors causing the symptoms. Usually such plants contain reserve nitrates and potassium.

Potassium

Use either stem or leaf tissues, preferably older tissues, and follow the procedure described for testing corn tissues for potassium.

A negative test for potassium indicates a deficiency and confirms any external symptoms that may be evident.

Methods for Preparing Reagents for the Chemical Tissue Tests

The reagents [3] for making the chemical tests on plant tissues for nitrates, phosphates and potassium referred to in this article are prepared as follows:

[3] The methods for preparing these reagents are taken directly from Purdue University Agricultural Experiment Station Circular 204 (37). Other workers have described methods for chemically analyzing plant tissues and the composition of the sap of various plants. Gilbert and Hardin (16), Pettinger et al., (29, 30, 31), Emmert (13), Hester (18), Morgan (26, 27), Thomas et al., (35, 36), Ulrich and others have described their respective techniques in detail. All involve the use of laboratory facilities and are very satisfactory for detailed comparative studies of healthy and malnourished plants of all kinds. These studies on the chemical compositions of plants provide facts not only for the interpretation of deficiency troubles, but also for the planning of extensive and effective programs for the fertilization of these crops. Canning companies and truck-crop growers are particularly interested in them.

Nitrate-Test Reagent

Dissolve 1 gram of diphenylamine in 100 cc. of concentrated sulfuric acid. Note: This solution is very corrosive and much care must be taken in using it. Do not use it if it becomes badly discolored—prepare a fresh solution.

Bray's Nitrate Test Powder should be used as indicated by the manufacturer.

Phosphate-Test Reagents

Reagent No. 1. Dissolve 4 grams of ammonium molybdate in 500 cc. of distilled water and add, slowly and with constant stirring, a mixture of 63 cc. of concentrated hydrochloric acid and 437 cc. of distilled water. As this solution may become unsuited for use after standing for a few months, it is desirable to prepare a solution of five times this concentration and dilute as needed.

Reagent No. 2. Dry powdered stannous chloride or stannous oxalate.

Potassium-Test Reagents

Reagent No. 1. Dissolve 5 grams of sodium cobaltinitrite and 30 grams of sodium nitrite in distilled water, add 5 cc. of glacial acetic acid, make to 100 cc. volume, and allow to stand for several days. Add 5 cc. of this solution to a solution of 15 grams of sodium nitrite in 100 cc. of distilled water and adjust to pH 5.0 with acetic acid. Sodium cobaltinitrite from different sources has been found to vary widely in cobalt content. The directions given here are based on the use of the Baker's Analyzed product. Cobaltinitrite concentration is an important factor in determining the sensitivity of the test.

Reagent No. 2. Ethyl alcohol (95 percent). When ethyl alcohol for use as a reagent is difficult to obtain, a mixture of 60 parts anhydrous methyl alcohol, 40 parts anhydrous isopropyl alcohol, and 5 parts of distilled water may be substituted. If this mixture becomes turbid it should be filtered. Completely denatured alcohol is not satisfactory.

Iron-Test Reagent

Prepare a 10-percent solution of potassium thiocyanate in distilled water. When ready to make the tests for iron in the joint tissues of the corn plant, mix 3 parts of this solution with 1 part of concentrated hydrochloric acid and apply several drops of the mixture directly to the tissues. This acidulated solution does not keep very well; prepare fresh mixtures when necessary. When used as indicated on page 72 a deep purplish-red color of the joint tissues indicates a severe deficiency of available potassium.

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Courtesy of North Carolina Agricultural Experiment Station, U. S. Department of Agriculture and American Potash Institute

Plate 1.—Left, severe nitrogen deficiency. Note yellowing begins at tip of lower leaves and proceeds up the midrib, giving a V-shaped pattern. Center, symptoms of extreme drought. As distinguished from nitrogen deficiency, drought affects upper as well as lower leaves. Severe potassium deficiency shows up in the plant on the right as a marginal scorch.

Courtesy of North Carolina Agricultural Experiment Station and U. S. Department of Agriculture

Plate 2.—Nitrogen made the difference! Nitrogen at the rate of 180 pounds per acre was applied to the corn on the left. The corn on the right received no added nitrogen. The yields were 110.3 and 24.4 bushels per acre, respectively.

A, courtesy of Florida Agricultural Experiment Station;
B and C, courtesy of Illinois Agricultural Experiment Station

Plate 3.—A, Zinc deficiency in corn. Advanced stage of "white bud" of the corn plant. The oldest leaves are dead, the upper leaves have yellow striping between the veins, and the plant is severely dwarfed. B, Calcium deficiency in corn. The tip ends of the leaves are gummed together. C, Phosphorus deficiency in corn. The yellowing of the leaves closely resembles that caused by nitrogen starvation. Tissue tests confirm phosphorus deficiency. D, Nitrogen-starved wheat. The yellowing of the tip ends and subsequent dying indicate nitrogen hunger. Nitrogen-starved leaves at right, normal leaf at left.

Plate 4.—Phosphorus hunger causes purpling of the leaves of many strains of corn.

Courtesy of Illinois Agricultural Experiment Station

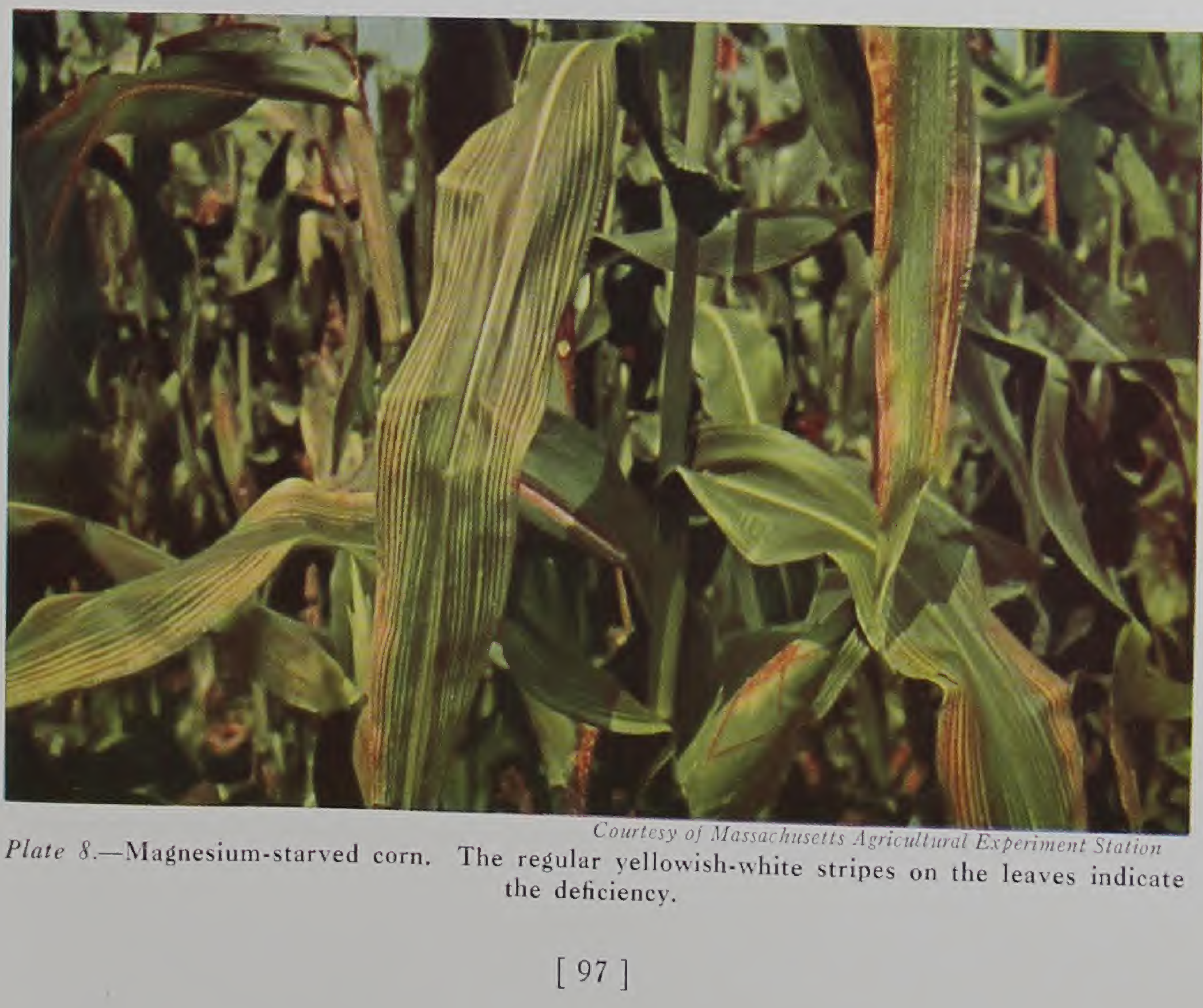
Plate 5.—Corn in the three pots to the left, inbred CC5, lacking the purple-pigment factor, does not develop purple color at 30, 10, or 5 parts of phosphorus per million. Corn in the three pots to right, inbred CC7, has the purple factor but develops slight color only at 5 parts of phosphorus per million (not at extreme right).

Courtesy of Illinois Agricultural Experiment Station

Plate 6.—Corn, inbred strain Hy, has the genetic factor for pigment production and the leaves become purple when starved for phosphorus.

Courtesy of North Carolina Agricultural Experiment Station and U. S. Department of Agriculture

Plate 7.—Potassium-starved young corn plant. The lower leaves show the typical marginal scorch. At this stage of growth in the field it is possible to apply remedial side dressings of potash salts profitably.



Courtesy of Massachusetts Agricultural Experiment Station

Plate 8.—Magnesium-starved corn. The regular yellowish-white stripes on the leaves indicate the deficiency.

A B C

Plate 9.—A, Normal corn leaf. B, Nitrogen-starved leaf. The yellowing begins at tip end and progresses along the midrib. C, Potassium-starved leaf. Note characteristic brown edge scorch.

Plate 10.—Potassium starvation results in weak corn stalks with the leaves badly damaged. The marginal "firing" affects all the leaves.

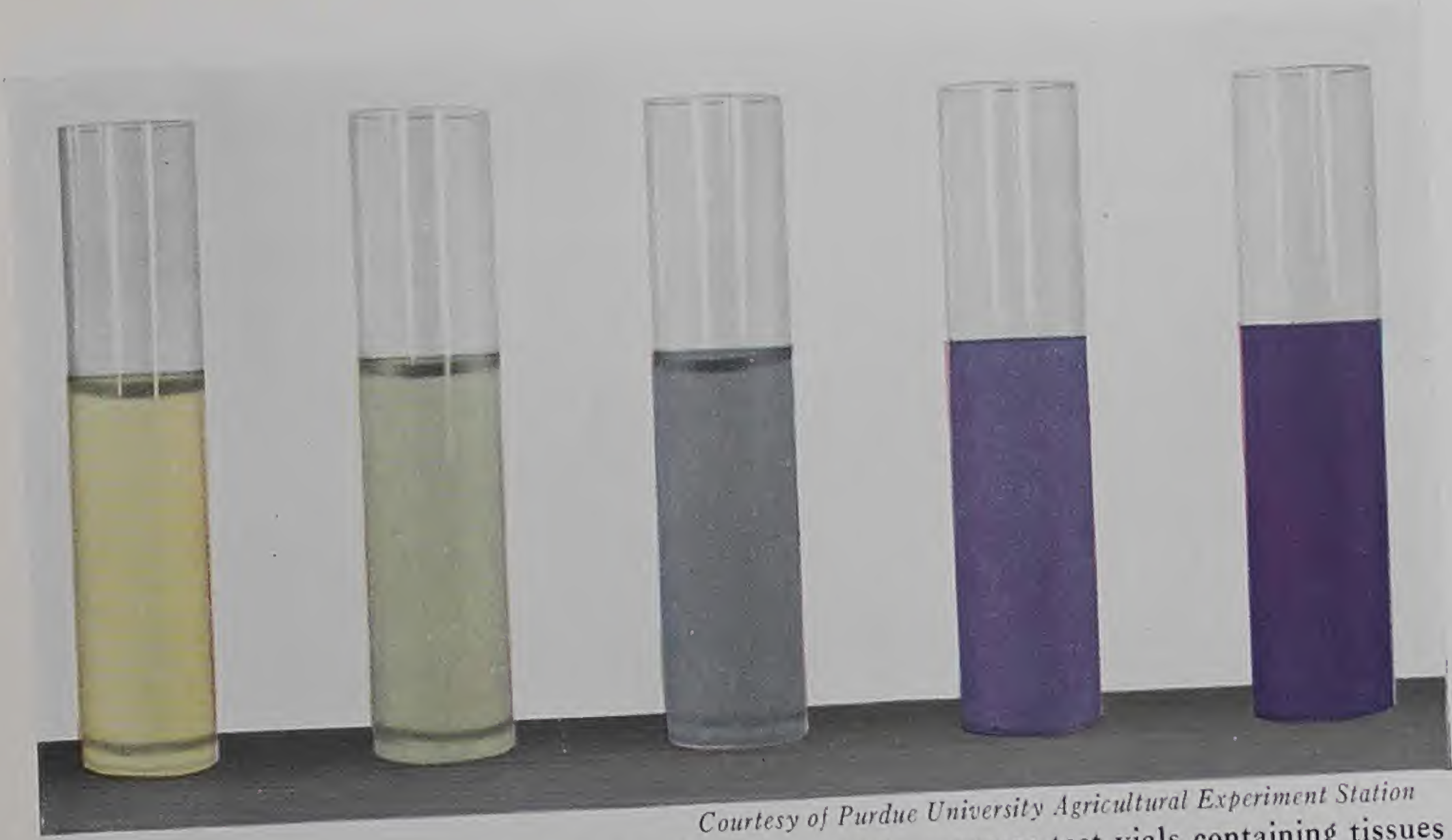
C and D, courtesy of Purdue University Agricultural Experiment Station

Plate 11.—A, Nitrogen-starved oat leaves. Nitrogen hunger causes the leaves to yellow and die. B, Phosphorus-starved oat leaves. The leaves die gradually from the tip ends with no particularly distinctive coloration. Note close similarity to the nitrogen-starved oat leaves. Chemical tests of the tissues are needed to confirm this symptom in the field. C, Magnesium-deficient wheat leaves. A slight mottling of the leaves was obtained in controlled nutrient cultures. D, Purplish-brown spots on barley leaves indicate potassium deficiency. These spots precede the usual marginal and tip-end "firing" of potassium-starved leaves. Cause of spots unknown.

Plate 12.—Nitrogen-starved oat plants. Yellowish-green plants seeded in disked corn stubble indicate a deficiency of nitrogen.

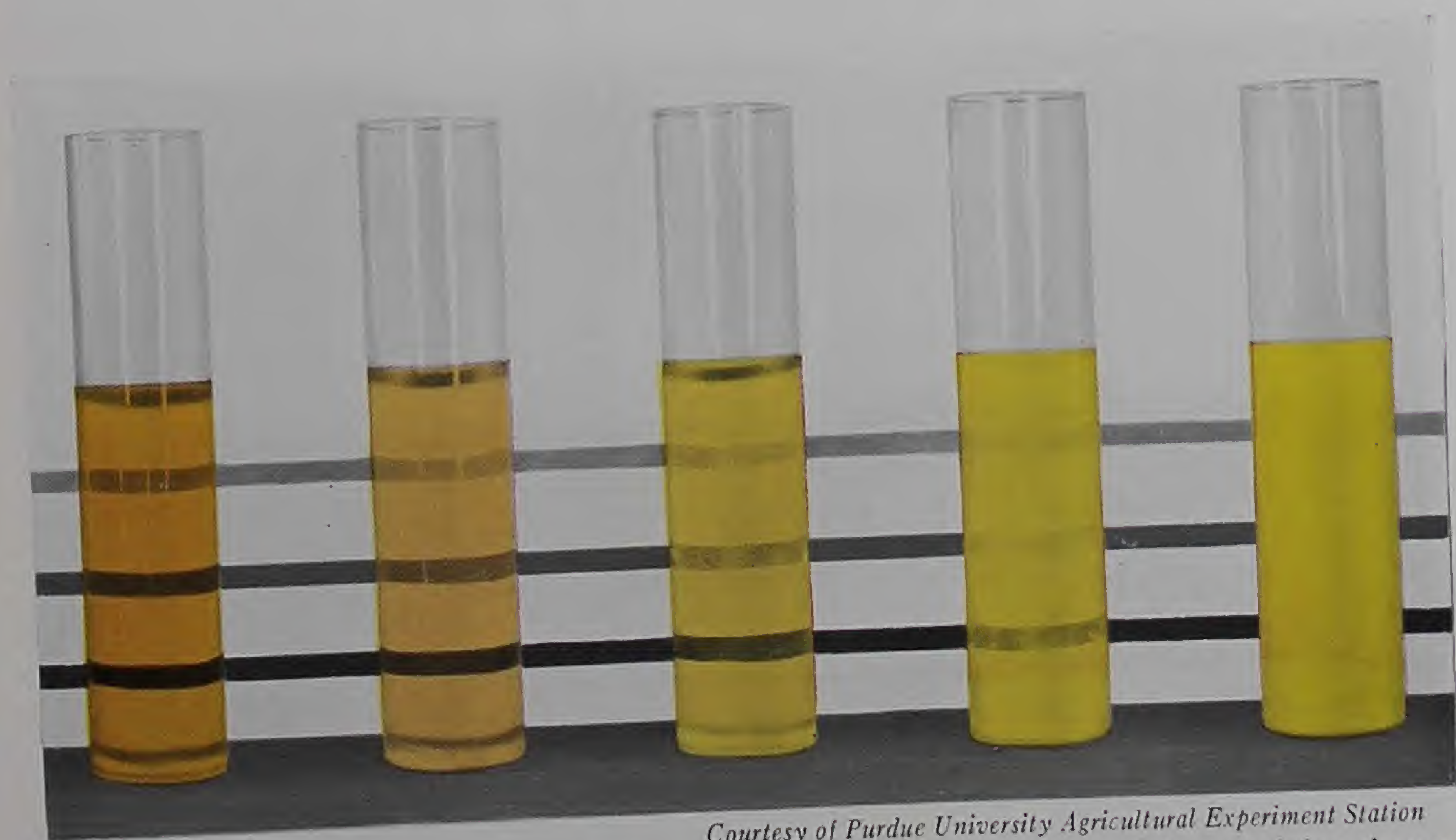
Courtesy of Eastern States Farmers' Exchange

Plate 13.—Magnesium-starved oat plants. The yellow-streaked, stunted plants indicate magnesium deficiency.



Courtesy of Purdue University Agricultural Experiment Station

Plate 15.—Phosphorus-test chart. When making tissue tests compare test vials containing tissues with those in the chart. The density of the blue color of the test solution indicates the relative content of inorganic phosphates in the tissues.



Courtesy of Purdue University Agricultural Experiment Station

Plate 16.—Potassium-test chart. When making tissue tests compare test vials containing tissues with those in the chart. The relative obliteration of the heavy black lines behind the test solution indicates the relative content of potassium in the tissues.

Plate 14.—A, Healthy green leaf of wheat showing balanced fertility. B, Yellowish-green leaf with tip end turning yellow indicates nitrogen starvation. C, Dark-green leaf with the tip end dying indicates possible deficiency of available phosphorus. D, Leaves with the tip ends becoming yellow and scorched along the edges indicates a deficiency of potassium. These symptoms are diagnosed with difficulty under field conditions unless chemical tests for nitrates, inorganic phosphates, and potassium are made on the tissues.

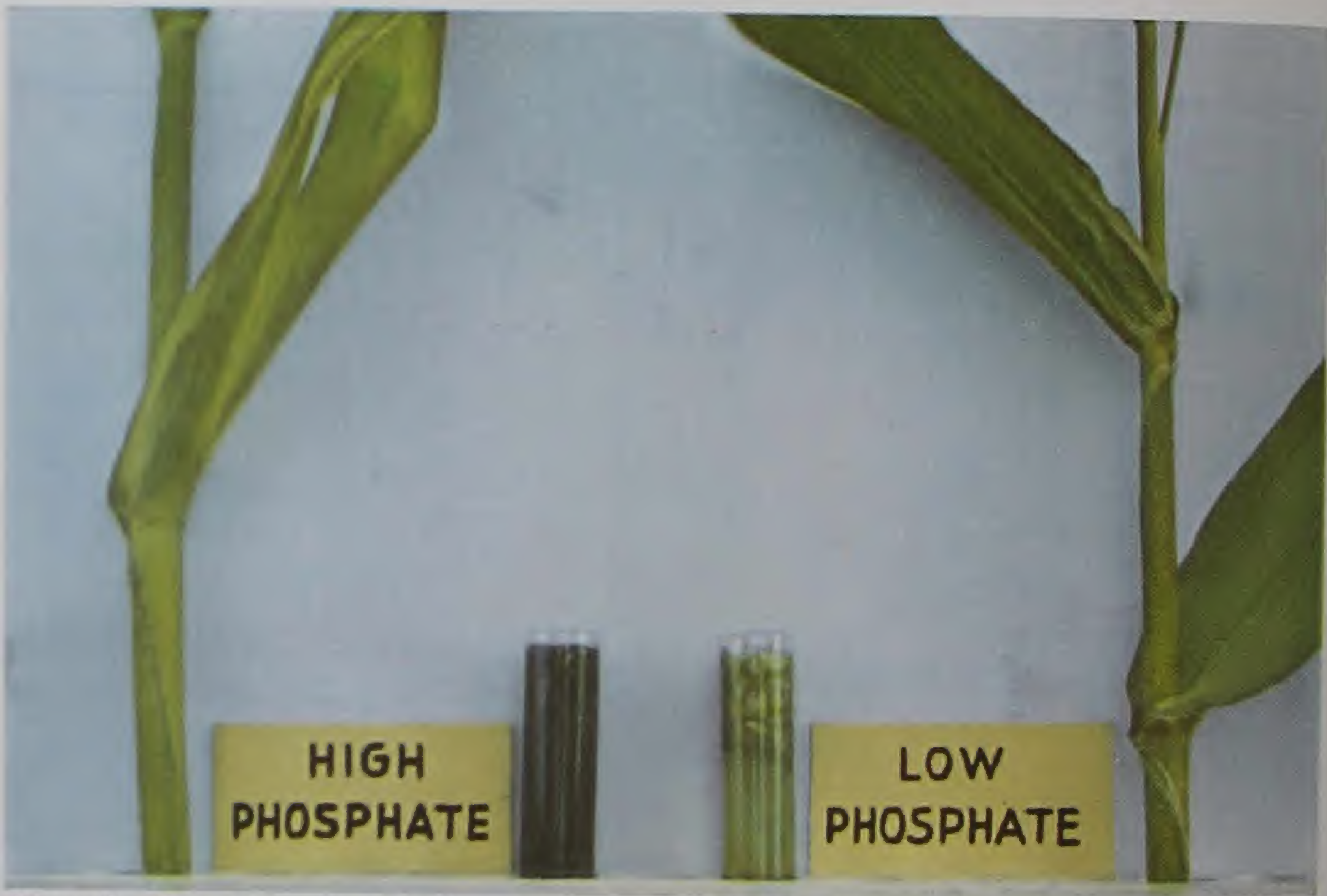


Plate 17.—Corn tissue test for inorganic phosphate. Left, high content of inorganic phosphate in stem tissues is indicated by the dark-blue color of the test solution in the vial. Right, a deficiency of inorganic phosphate is indicated by the light greenish-blue color of the test solution. The plants showed no definite symptoms to indicate these tissue-test differences other than in their relative sizes.

Plate 18.—Corn tissue test for potassium. Left, healthy leaf tissues contain an abundance of potassium, as shown by heavy turbidity of test solution in the vial. Right, the marginal-scorch symptom is confirmed by the negative (clear solution) test for potassium in the leaf tissues.

Courtesy of American Potash Institute

Plate 19.—Demonstration of tissue tests used for the confirmation of nitrogen and potash deficiency symptoms in hybrid corn plants.

(A). Leaf and ear from a well-nourished plant. Note healthy leaf and well-matured ear. Tissue tests are shown as follows:

(1) Medium nitrate—red color—with Bray's nitrate test powder. See Selected Reference 4, for description.

(2) Medium potash—see plates 16 and 18.

(3) Medium phosphate—see plates 15 and 17. Compare these healthy tissue tests with (B) and (C).

(B). Nitrogen-deficient plant. Note yellowish green leaf and deadened tissue along midrib. Also glossy kernels on underdeveloped ear. These kernels are low in protein, but high in fats.

(4) *Negative nitrate*—no color.

(5) Very high phosphate.

(6) Very high potash. Nitrogen-starved plants frequently accumulate luxury amounts of phosphate and/or potassium as shown in these tests.

(C). Potassium-deficient plant. Note the deadened marginal leaf tissues and the tapered, unfilled ear with starchy kernels.

(7) Very high nitrate—deep red color.

(8) Very high phosphate.

(9) *Low potash.* Potassium-deficient plants will accumulate luxury amounts of nitrates and/or phosphates, but cannot function properly in producing mature ears.

These tissue tests show that when one plant nutrient becomes deficient, other nutrients may accumulate in excessive amounts further to complicate the diagnosis of the "deficient plant." Luxury quantities of nitrates (7), phosphates (5, 8), and/or potash (6) frequently indicate a deficiency of some other essential nutrient for healthy growth and development of the plant.

It is imperative to use all possible tests for the nutrient elements correctly to diagnose deficiency symptoms. For example, the very high phosphate tests (5, 8) may be misleading when nitrates and/or potassium are deficient in the plants tested. Medium tests for nitrates (1), phosphates (3) and potash (2) indicate adequate amounts in the plants at the time of testing. They are particularly important when the ears are maturing, in order to ascertain whether all of the plant nutrients were adequately supplied in the fertilizers applied to the crop.

CHAPTER IV

Plant-Nutrient Deficiency Symptoms in the Potato

By H. A. Jones, B. E. Brown and G. V. C. Houghland [1]

THE needs of the potato for the different nutrient elements are about the same as those of other crop plants, but this does not necessarily imply that the potato requires a given element in the same quantity as other plants. The potato may not have as big an appetite for certain elements as do other crops. Take, for example, the element boron. Some crops, including celery, cauliflower, turnips and the sugar beet, appear to be much more susceptible to boron deficiency than is the potato. The greater response of cauliflower to boron has been used to ascertain whether a deficiency of boron could be detected in potato fields. This was accomplished by "spotting" cauliflower plants in the fields. Failure to produce symptoms was assurance that boron was not deficient.

One may make a conjecture about the soil conditions responsible for nutrient deficiencies, but the forces at work are often apt to be so insidious that the final crop disturbance may not manifest itself definitely for some time. For example, when magnesium deficiency began to develop in a number of important potato-producing sections along the Atlantic seaboard, it was not until the supply of available magnesium hit rock bottom that definite symptoms of magnesium deficiency were generally observed. The continued use of certain fertilizers tended to increase the acidity, and the trouble spread rapidly. After considerable experimental work the remedy was found to be the addition of magnesium to the fertilizer mixture or directly to the soil. Combining the magnesium compound with the fertilizer gave a quicker effect and insured a supply of magnesium for the young potato plants.

The writers have been unable to find a single case reported in the United States of a deficiency of boron, calcium, copper or zinc which has affected the potato when grown under field conditions. However, salts containing these elements have been applied to potato soils in this country with results differing from little to no response,

[1] H. A. Jones is head horticulturist, B. E. Brown is formerly senior biochemist, and G. V. C. Houghland is biochemist, Division of Fruit and Vegetable Crops and Diseases, Bureau of Plant Industry, Soils and Agricultural Engineering, U. S. Department of Agriculture.

and in a few cases actually causing depressions in growth and yield (3, 11, 12, 13, 15, 16, 19, 20, 22, 23, 24, 27). Manganese deficiency has been reported in naturally calcareous or overlimed soils because under such conditions this element is made comparatively unavailable for use by plants (10). Other elements—boron and zinc—are

Figure 1.—Above, potato vines free from any nutrient deficiency. Normal foliage and growth. Splendid yields are the result of careful culture and plant feeding. Below, potato vines responsible for such a yield as this received a well-balanced diet with no deficiency of any nutrient element.

reported to be affected similarly by an excess of calcium carbonate (21). Potato soils in the East, however, are generally acid in reaction, and perhaps this is why boron and zinc deficiencies are not a problem. For the same reason iron and manganese present no problem. Spray programs tend to provide a supply of copper and arsenic. In the more detailed discussion to follow, no reference has been made to aluminum, molybdenum and a number of other so-called minor elements because there is no evidence at the present time to indicate

that they are essential to the potato. The time may come, however, when an element not now established as essential may turn out to be a vital factor in potato production. Potato investigators must be alert to the importance of the many studies under way to determine the requirements of economic crops for these minor elements, and be ready to determine the bearing these studies may have on potato production.

The white or Irish potato is adapted to a wide range of soil and climatic conditions. In the United States it thrives from Maine to the lower Rio Grande Valley of Texas, and from the Atlantic to the Pacific coast (figure 1). Important commercial-producing districts, presenting a wide variety of growth conditions, are located in areas of both high and low altitudes and humid and semiarid conditions. In these districts crops are grown with different lengths of daylight, under sunlight of different qualities and intensities, and on soils that vary widely in texture and in natural fertility. To each environmental influence the potato plant responds in a somewhat different manner. Deficiency symptoms due to the lack of any one or more than one element are not always the same under all conditions, but certain of the abnormalities seem to be characteristic, and these will be given consideration here.

When the plants are grown under controlled conditions in sand and water cultures there is much better agreement in the descriptions of the deficiency symptoms observed by various investigators. These artificially produced symptoms help to point the way to a finer differentiation of deficiency symptoms occurring naturally under field conditions.

NITROGEN DEFICIENCY

A deficiency of available nitrogen is a distinctly limiting factor in the growth of the potato plant—perhaps more generally so than a deficiency of any other essential element. Some source of nitrogen—manure, commercial fertilizer, green-manure crops, or a combination of these—is almost always utilized in commercial potato production, except possibly on organic soils, such as muck and peat.

In Virginia an acre of potato plants during the first 50 days after planting utilized less than 7 pounds of nitrogen as measured in the growth above ground; during the next 10-day period absorption of nitrogen averaged 1 pound a day, and during the next 20-day period it averaged 2 pounds a day. After about the eightieth day, when growth above ground had practically stopped, there occurred a

gradual transfer of nitrogen from the foliage to the developing tubers (6).[2]

The reaction of the potato to nitrogen deficiency is similar to that of many other crops. The growth of the entire plant is restricted in accordance with the extent of the deficiency (plate 1, page 129), and this stunted condition is reflected in reduced yields and poor quality of tubers. The plant takes on a light-green to yellowish-green color. In advanced stages, the margins of the lower leaflets lose their chlorophyll, the color fading to a pale yellow (plate 1, lower right), and some shedding of foliage usually results.

Nitrogen deficiency is usually associated with sandy soils low in organic matter and acid enough to interfere with nitrification. A fertilizer practice that fails to offset the nitrogen losses from the soil, as a rule, ultimately results in acute nitrogen deficiency. Preventive measures include liming to control soil reaction; adding nitrogen-organic matter in the form of manure, composts and green manures to supply a reservoir of nitrogen; and using commercial fertilizer at the proper time and rate to provide an ample supply of available nitrogen.

PHOSPHORUS DEFICIENCY

Phosphorus absorption during the season corresponds closely with that of nitrogen, but the greatest amount of phosphorus absorbed is about one-sixth that of nitrogen in Virginia (6) and one-twelfth that of nitrogen in Maine (14). At the time the plants reach full growth, about 50 to 75 percent of the phosphorus in the tops has been conducted to the developing tubers (6, 14). A supply of phosphorus which is inadequate generally causes pronounced growth reactions (plate 3, page 130). The plants are smaller than normal, somewhat spindling, and definitely retarded in growth, particularly during the early stage of development. At Aroostook Farm, Presque Isle, Maine, plants on plots receiving ample quantities of nitrogen and potassium but no phosphorus grow very slowly during the early part of the season and often appear no better and occasionally poorer than those on plots without fertilizer; but later, when they have developed a more extensive root system, they outgrow the plants without fertilizer. They also tend to continue growth in the fall longer than those on most of the other plots.

[2] The list of citations at the close of this chapter is by no means complete. Anyone interested in more extensive reading is referred to "Bibliography of the Literature on the Minor Elements and Their Relation to Plant and Animal Nutrition," fourth edition, Volume I, 1948, published by the Chilean Nitrate Educational Bureau, Inc., 120 Broadway, New York 5, N. Y.

Potato plants grown on phosphorus-deficient soil may produce tubers with rusty-brown lesions in the flesh in the form of isolated flecks which sometimes join together to produce larger discolored areas. The flecks occur in both the cortex, or outer region, and the pith, or central portion, and may cross the vascular ring located between these two regions. Generally, the pith is affected more often than the cortex. The flecks vary in size from those that are scarcely visible to those almost half an inch in diameter. They also vary in number. If the crop is lightly affected, only a single small fleck may be apparent in a tuber; if it is badly affected, the lesions may occupy more than half the volume of the potato. The arrangement of the flecks is generally irregular, but occasionally there is a tendency toward a radial pattern—streaks running out from a center. In external appearance there is usually no distinction between normal and affected tubers. Seldom do flecks occur so near the surface that they can be seen without cutting. When these potatoes are boiled, the flecks remain as hard, discolored masses in the softened tissue. Brown flecks in the flesh of potato tubers have been described in the publications from most potato-growing countries. However, brown flecks may be due to other causes besides phosphorus deficiency—for example, virus diseases or heat or frost injury.

When potato plants are grown in sand or water cultures with solutions deficient in phosphorus (plate 2, page 130), the leafstalks (petioles), leaflets and their margins turn upward. The leaflets are smaller and darker than normal, and the plants are somewhat rigid (17, 26).

Phosphorus deficiency occurs on a wide range of soil types—on heavy soils because of fixation, which makes the phosphorus unavailable; on light soils because of a naturally low phosphorus content; and on both types because of crop removal. Lack of available phosphorus may be reflected more in low yields and poor quality than in distinctive foliage symptoms, but the latter will develop where continuous cropping is practiced without adequate phosphorus applications.

POTASSIUM DEFICIENCY

The potato plant must have a continuous supply of potassium for normal growth. Where a deficiency exists, growth of the plant is first retarded and finally completely checked, and the internodes are somewhat shortened, which gives the plant a compact appearance.

The leaves are reduced in size, owing to a narrow arrangement of the leaflets, which form a sharper angle with the leaf petiole. The leaflets lose their smooth surface, become crinkled and curve downward.

The early appearance of abnormally dark green foliage is one of the most dependable signs of potassium hunger. Then the older leaves become yellowish, and a brown or bronze color develops, starting from the tip and edge and gradually affecting the entire

Figure 2.—The final stage of potassium hunger—a plant completely collapsed through lack of vigor and resultant fungus attacks. Only small, low-quality tubers are produced by such plants.

leaf, which finally dies (plate 4, page 131). In a single plant this bronzing is not so striking, but it is quite prominent in mass effect. Under certain light conditions a distinct purplish cast is apparent. A number of the lower leaves may dry up at the same time, leaving for a time a tuft of dark-green leaves at the apex, or top, of the plant. Eventually, the entire plant dies (figure 2).

Sand cultures have also been used to study potassium-deficiency symptoms of the potato, and the responses reported are similar to those described for plants growing in the field (26). The leaf, leaflets and leaflet margins bend downward. The color of the leaves changes from a normal healthy green to a dark green and afterwards to a peculiar bronze or yellow, beginning with the oldest leaves.

Symptoms on the lower leaves may be pronounced while the top of the plant still has a normal appearance. The diseased tissue of the leaves protrudes strongly between the veins. In severe cases the leaf margins break down, and discolored areas appear on various parts of the stems and petioles. The tuber stolons are shorter than normal, and the roots and tubers are poorly developed.

Figure 3.—During World War I potash became a scarce article. Rows on left received 5-10-0 at rate of 1 ton per acre; rows on right, 4-8-4 at the same rate. Much earlier collapse of plants where no potash was in the mixture is very evident.

Yields are decreased in proportion as the shortage of potassium increases. In the United States the area most generally affected is that lying east of the Appalachian Mountains, particularly the sandy soils of the Atlantic Coast States. Deficiency symptoms have been noted as far north as Aroostook County, Maine, being more prominent there on the Washburn than on the Caribou type of soil. In general, deficiency occurs on light sandy soils of a leachy nature and on mucks and peats. Some heavy soils high in total potassium, however, are too low in available potassium to satisfy the needs of the potato crop, which requires from 100 to 200 pounds of potash per acre. During World War I, when the supply of potash fertilizer became very low, the deficiency became very serious (figure 3).

premature death of many plants and greatly reduced yields, was probably caused by the more critical need of the plants and tubers for magnesium as the season advanced.

In Holland, when the potato variety President was grown under controlled conditions in glass sand in the absence of magnesium, the symptoms were more severe but similar to those observed in the field (26). Chlorosis developed at the tips of the lowermost leaves, then advanced along the margins and between the veins until the entire leaf was involved. The terminal leaflet was attacked first, then the other leaflets. Chlorosis progressed from the lowermost leaves upward, and in severe cases only the youngest leaves at the top remained green. The older leaves died prematurely, beginning at the tip and margin of the terminal leaflet. In severe cases the chlorotic tissue was almost pure white and protruded upward, while the tips and margins of the diseased leaflets bent downward. Growth of roots and tubers was also checked. In the presence of excess nitrogen, symptoms were still more severe.

Magnesium deficiency is associated with a combination of very low magnesium content, rather low calcium content, and relatively high nitrogen content in the lower leaves. In normal aging, the lower leaves have a high content of magnesium and calcium but are low in nitrogen (6). Investigations in Virginia have shown that symptoms of magnesium deficiency do not appear in plants containing over 0.4 per cent of magnesium oxide; but under conditions of excessive rainfall during the early months of the potato-growing season, coupled with the heavy use of acid-forming fertilizer, magnesium probably becomes a limiting factor on even the most fertile types of potato soil (7).

Results of experiments in Aroostook County, Maine, have shown that the so-called "potato sickness" prevalent in that district and specifically associated with magnesium deficiency may be effectively controlled by applying a magnesium compound to the soil. Substantial increases in the yield of Green Mountains and Irish Cobblers were obtained by incorporating magnesium sulfate[3] with the ordinary potato fertilizer (8, 9), or in the spray mixture (2), particularly in fields where severe chlorosis developed shortly after the emergence of the plants. Deficient plants sprayed with magnesium bordeaux showed recovery in the new growth, lived longer, and yielded more. In one test the yield from the use of magnesium bordeaux was 96 bushels an acre more than the yield in adjacent

[3] Equivalent to 30 pounds of magnesium oxide (MgO) per acre.

Fortunately, this country need no longer fear the pinch of potash hunger.

Obviously the remedy for potassium deficiency as it affects the potato is to utilize any available manure or fertilizer containing sufficient available potassium.

MAGNESIUM DEFICIENCY

Magnesium-deficiency symptoms on potatoes have been reported from practically all of the potato districts of the Atlantic Coastal Plain and as far north as Aroostook County, Maine.

The foliage of affected plants is lighter in color than normal. The lower leaves are the first to become affected, since some of the magnesium is withdrawn to be used over again by the new growth. In mild cases, only the lower leaves of the plants show symptoms, while the new growth appears healthy. Loss of green color begins at the tips and margins of the lowermost leaves and progresses between the veins toward the center of the leaflets. In advanced stages of deficiency the central portion of the individual leaflet becomes chlorotic between the veins and eventually is filled with small brown dead areas. Breakdown of the tissue, like loss of color, usually starts at the tip of the leaf, and the terminal leaflet is generally the one most severely affected. The lower leaves of magnesium-deficient plants are brittle, which serves to distinguish them from leaves yellowing naturally through age.

In severe cases nearly the entire area of the leaves and all except the top growth of the plant are affected. The plants have a very marked chlorotic and stunted appearance with some upward rolling of the lower leaves, which show a definite bulging between the veins and become thick and brittle. These symptoms seem to be most conspicuous after a warm, dry spell when the potato plants are about 8-10 inches tall. Finally, the chlorotic leaves die, turn brown, and often drop off the plant (plate 5, page 132).

Magnesium-deficiency symptoms were observed in Virginia in 1931 at two distinct periods in the growth of the crop (7). Indications of the trouble were detected first in late April, during a period of rainy weather when foliage growth was rapid. Later, during a dry spell, the trouble disappeared to some extent as the plants were able to absorb sufficient amounts of magnesium from the soil. Deficiency symptoms appeared again during the latter part of May and were prevalent over a much wider area than at the time of the first outbreak. The recurrence of symptoms, which resulted in the

plots sprayed with high-calcium bordeaux. On less deficient soil in the same field, the yield was increased only 38 bushels per acre. In another test the magnesium bordeaux increased the yield 133 percent on deficient soil and 11 percent on better soil. It is suggested that some of the spray stimulation reported in the past may have been due to absorption of magnesium by the plants from magnesium lime in the bordeaux.

Magnesium deficiency generally occurs in highly acid soils, but it is not necessarily confined to those that are light and sandy, for its effects have been observed on soils of high fertility such as Caribou loam in Aroostook County. Heavy applications of acid-forming fertilizers, particularly those containing certain nitrogen materials of high plant-food concentration, increased the solubility of the magnesium compounds, which were subsequently leached away from the feeding range of the young potato plants.

Practical remedies for magnesium deficiency consist of applications of light amounts of dolomitic limestone made directly to the soil; introduction of magnesium sulfate, generally a calcined form, into the fertilizer mixture, at a rate to furnish 30 to 40 pounds of magnesium oxide per ton; addition of enough dolomitic limestone to the fertilizer mixture to make it neutral; or a combination of two or more of these (18). The use of magnesium bordeaux or spraying the tops with a 2 to 3 percent solution of magnesium sulfate is a quick-acting remedy, but soil applications produce a more lasting effect.

CALCIUM DEFICIENCY

Though only about one-fourth as much calcium as potassium is used by the potato plant, calcium plays an important part in the plant's development besides creating a favorable soil environment for growth (6). Calcium has an indirect effect on the growth of the plant by altering the availability of certain nutrients and preventing the toxic effect of others.

Potatoes grow well in acid soils—pH values between 4.8 and 5.5. When the soil is more acid than this, unfavorable conditions develop, such as aluminum toxicity and phosphate fixation. Soils less acid may prove congenial for the growth of the scab organism; though yields may not be reduced, the scabby tubers are less desirable for market and the crop may even be valueless because of scab lesions.

The intake of calcium into the aerial portion of the potato plant is continuous, and the amount present reaches its peak at maturity.

There appears to be very little removal of calcium from the older portions of the plant to the developing buds and shoots, and for this reason a continuous supply of available calcium from the soil to the growing regions of the plant is necessary if deficiencies are not to occur. Also, the transfer of calcium from the aerial portion to the developing tubers seems to be negligible. Studies in Virginia show that only about 7 percent of all the calcium absorbed by the plant is located in the tubers (6).

One would naturally expect to find calcium-deficiency symptoms in the potato plant in regions where acid soils and heavy rainfall prevail. Though such symptoms apparently have not been observed or reported in the literature, the possibility remains that certain abnormalities that have been ascribed to other causes may have been due to lack of calcium. Because of lack of evidence under field conditions, it is necessary to refer to calcium-deficiency symptoms induced artificially (plate 6, page 133).

Deficiency symptoms on potato plants grown in sand culture with limited calcium are characteristic and pronounced (26). First, a light-green band appears along the margins of the young leaves of the bud. The tissue in these light-colored areas may be killed; consequently, the leaves do not develop normally and often have a wrinkled appearance. In severe cases the young leaves at the top remain folded and later the tip of the plant dies. The axillary growth which develops later may show the same symptoms as did the young leaves of the terminal bud.

In the medullary or pith region of the tubers, dead spots develop; these areas show first as a diffuse brown discoloration within the vascular ring at the stem end of the tuber. The symptoms may show up in tubers from plants that had healthy-looking foliage, which seems to indicate that when calcium becomes deficient late in the life of the plant the effect is primarily on the tuber, there being very little or no transfer of calcium from the aerial portions of the plant to the tubers to take care of the deficiency. Thus a continuous supply of calcium must be available as long as new organs are being formed and new tissue is being developed.

Calcium deficiency usually develops later in the growth of the plant than magnesium deficiency, owing to differences in solubility and leaching of the respective compounds. Potatoes growing on light sandy soils, which are more nearly devoid of calcium compounds than heavier soils, generally suffer first. The obvious remedies are to prevent excessive acidity by the use of limestone and to incor-

porate suitable calcium compounds with the fertilizer mixture when these are known to be lacking in the materials used.

BORON DEFICIENCY

Boron-deficiency symptoms of potatoes have been reported from time to time. In the field they have been described as occurring chiefly in tubers rather than on the vines. Only minute quantities of boron are needed for normal growth, and, so far as known, there are few published reports of vine injury under field conditions due to the lack of this element. Where a deficiency of boron does exist, field applications have given noticeable growth responses, such as hastening the emergence of the plants and bringing plants into bloom 10 to 14 days before those without boron applications.

A report of field experiments by the New York (Cornell) Agricultural Experiment Station indicates that boiled potato tubers grown without boron additions to the soil showed much sloughing (falling away of outer layer), were fairly soggy, and possessed a flat flavor definitely inferior to that of tubers grown with added boron. The effects of adding 20 pounds of borax per acre were to produce a material reduction in sloughing, an increase in mealiness and dryness, and an improvement in texture, flavor and color (25). However, the quality of dehydrated potatoes, including their color and flavor, was reported to be unaffected by applications of 7½ pounds of borax per acre contained in potato fertilizer (5).

During the World War I period and for a time following, considerable injury occurred to the potato crop from excess amounts of borax in fertilizers. Subsequent experiments have shown, however, that bad effects on yield may be due largely to the manner in which borax is applied. On Caribou loam in Aroostook County, Maine, definite injury occurred when 5 pounds per acre were applied in the furrow directly before planting. Surplus borax may prevent sprouting of the seedpiece and thereby produce poor stands. Other effects are killing of the sprouts after some growth has occurred, failure of roots to form, weak appearance of plants that finally do emerge, bleaching of the foliage or marginal yellowing of the leaves, and abnormally low yields (4).

Because of the inability to study satisfactorily the effect of boron deficiency on the behavior of the potato plant under field conditions, a number of investigators in both Europe and America have designed experiments whereby the plants could be grown with insufficient boron in water and sand cultures. It is doubtful, however, if many

of the symptoms that appear in culture will ever appear in the field, because such a minute amount of this element is adequate for the normal functioning of the plant (plate 7, page 133).

The descriptive reports of most investigators regarding deficiency symptoms are in fairly close agreement. A killing of the growing points and the tips of the terminal shoots and a stimulation in growth

Courtesy of the New York (Cornell) Agricultural Experiment Station

Figure 4.—Lack of sufficient boron seriously interferes with root development of the potato plant. Fibrous roots are seen to be very much restricted in growth. (From work of Ora Smith and L. B. Nash.)

of the lateral buds are characteristic. Internodes remain short and give the plant a short, bushy appearance. Leaves thicken and the margins roll upward, as in potato leaf roll. When the boron deficiency is not great, only a slight upward curling of the leaf margins of the older leaves is visible. With greater deficiency petioles become brittle, loss of green color (chlorosis) appears, and in severe cases anthocyanin (a purple pigment) is developed. The leaf points and margins, especially those of the older leaves, die prematurely. Starch congestion in the leaf tissue is conspicuous.

In an advanced stage of boron deficiency the roots are short and thick and have a brown appearance. Root tips die, and this stimu-

lates the development of secondary rootlets, which in turn may die soon after emergence (figure 4).

Internal symptoms of boron deficiency are first found at the growing points of the roots and afterwards at the growing point of the stem. These symptoms appear as a brown discoloration and a breaking down of individual cells or cell complexes before the growing point is killed. Later, the stem, the axillary buds, and the internal parts of the lateral shoots become diseased; next, the tissue of the nodes is attacked, that of the highest first, then that of the internodes.

Boron-deficient tubers are smaller than normal and often have a ruptured surface. The green portion of the plant may be markedly diseased, whereas the tissue within the tuber may show slight symptoms or none at all. Again, the tubers may develop typical symptoms, such as a local brown discoloration below the skin, generally at the stem end of the tuber, or a brown discoloration of the vascular ring—most pronounced at the stem end but varying in the distance it extends toward the apex—or both. In a few cases portions of the pith region also were reported as having been affected with brown discolorations.

Boron deficiency has not as yet become a problem for the potato grower unless boron is needed to prevent certain physiological disturbances within the tubers themselves. More experimental work will be required to determine whether the results reported by European investigators are applicable to conditions in the United States. Although authentic cases of boron deficiency have not been observed in the United States in the field, it is felt that under certain conditions a light broadcast application—10 to 15 pounds per acre—of sodium borate (ordinary borax) may be beneficial.

MANGANESE DEFICIENCY

Manganese has long been known to be present in plants, and in comparatively recent years it has been considered an essential element for plant growth (figure 5). This element has been shown to function in the synthesis of the green coloring matter (chlorophyll) and in photosynthesis—the manufacture of carbohydrate in the plant. To manganese are also ascribed certain stimulating (catalytic) functions, such as the activation of oxidizing enzymes. These functions would seem particularly important in the potato.

Symptoms of manganese deficiency have been noted especially in plants grown on highly calcareous or marly soils or on those that have been heavily overlimed. The first symptom is a chlorotic

condition of the leaves, appearing first between the veins as an abnormal coloration which, depending upon the kind of plant, may be either pale green, yellow or red. Usually as the trouble becomes intensified the discolored areas between the green veins turn white (plate 8, page 134). In Australia it has been shown that the "gray speck" or "white wilt" malnutritional disturbance of oats is associated with a lack of available manganese.

Courtesy of J. R. Neller, Florida Agricultural Experiment Station

Figure 5.—When the supply of manganese is insufficient, potato plants show it. Above, not enough manganese; below, enough manganese.

Manganese deficiency has been noted on certain truck soils of the Atlantic seaboard, but no clear-cut description of how it affects the potato has been given (1, 10).

In water culture the deficiency symptoms on potatoes appear as light-green chlorotic areas in the interveinal tissue of the upper leaves. Later, numerous little brown patches develop along the veins and these dead areas increase in both size and number. When the lack of manganese is not severe, the upper parts of the plants become somewhat chlorotic but do not develop dead spots (plate 9, page 134).

Even on highly calcareous or heavily overlimed soils it is likely that 50 to 75 pounds of manganese sulfate per acre would be sufficient to meet any deficiency of this element. On acid soil there may

be an excess of manganese in the soil solution sometimes great enough to create a toxic condition.

SULFUR DEFICIENCY

Sulfur-deficiency symptoms in the potato appear to have been encountered in the United States only in nutrient culture studies (figure 6). No symptoms on potatoes seem ever to have been

Courtesy of U. S. Department of Agriculture

Figure 6.—Normal potato plant at right. The plant at the left is exhibiting pronounced sulfur-deficiency symptoms. The leaves and veins are yellowish with slight upward roll, and small brown necrotic areas occur between the veins.

observed under field conditions in this country. Until recent years the general use of superphosphate as a source of phosphorus in mixed fertilizers has been an insurance against sulfur hunger. Observations on other plants show that when a shortage of sulfur exists the leaves may become yellow, the stems woody, and root development may decrease. Sulfates have been found to increase nodular development of certain legumes, notably alfalfa and red clover. Other researches tend to show that sulfur increases root development and may have a role in chlorophyll development. Most investigations seem to indicate that symptoms resulting from a shortage of sulfur develop slowly.

In sections where fertilizers containing ordinary superphosphate are used in potato production, the large quantity of calcium sulfate

associated with the superphosphate is insurance against a shortage of sulfur. If, however, concentrated fertilizers are used which contain no sulfur compound, a deficiency on light sandy soils may develop. Obviously, the inclusion of appropriate sulfur compounds in these fertilizer mixtures would then be necessary.

IRON DEFICIENCY

A deficiency of available iron results in a malnutritional chlorosis which requires treatment with an iron salt to overcome the conditions or at least to prevent further development. Like those of boron, manganese and zinc, iron deficiency is usually found on highly calcareous or overlimed soils. This condition makes the iron less available and causes a so-called lime-induced chlorosis. On acid soils a deficiency of iron is a very remote possibility. A search of the agricultural literature fails to disclose any description of iron-deficiency symptoms in relation to potato plants in the field.

In water culture, with iron omitted the first symptom on potatoes is a slight chlorosis in the young leaves, rather regularly spread over the leaf blade. The points and margins of the leaflets keep their green color longest. Since both the green and yellow pigments are affected, the discolored tissue becomes a clear pale yellow, and in extreme cases almost pure white. The chlorotic tissue is curved in an upward direction. Leaves that develop before the symptom appears retain a normal green color.

Iron deficiency has not been reported on potato soils so far as is known. On acid soils there is usually sufficient available iron in the soil solution to take care of growth requirements. As acid soils are usually preferred by potato growers because of the inhibitory effect on the development of the scab organism, there is little possibility of iron deficiency occurring in the production of this crop. To correct iron deficiency in other crops, the salt most generally used is ferrous sulfate.

COPPER DEFICIENCY

Copper is now considered by some to be essential to plant growth, but convincing proof is still lacking as to whether it is essential or indirectly beneficial. No authentic case of copper hunger except on organic soils seems to have been recorded in the agricultural literature. Potato soils of a mineral type rarely, if ever, suffer from lack of copper. This perhaps may be ascribable to the fact that sufficient copper is applied to potato plants in spray mixtures to prevent a

deficiency. Some of the added copper gets into the soil, while some may be absorbed by the potato foliage.

Copper deficiency has not been known to occur in the general run of potato soils. As mentioned, potato plants have for their utilization the natural store of copper in the soil supplemented by the copper in sprays applied to prevent fungus diseases.

Copper sulfate is the copper salt usually applied to the soil to correct a deficiency of this element.

ZINC DEFICIENCY

Zinc is now accepted provisionally as an element essential for plant growth. Very little of this element apparently is required by plants. Present knowledge, however, indicates that some plants either need less zinc than others, or are able to obtain their needed supply more readily through a more elaborate root system. So far as is known, zinc-deficiency symptoms have never been reported as occurring on the potato under field conditions. Very little of a positive nature is known about the metabolic activities of zinc, some investigators adhering to the belief that its action is indirect.

Potato plants growing in water cultures without zinc are reported to show distinct deficiency symptoms. Growth of the plants is checked and they do not attain as large a size as those supplied with zinc; the top leaves assume a slightly vertical position, while the margins of some of the leaflets curl slightly upward suggesting the early symptoms of leaf roll. The leaves are smaller than those of the controls, the upper internodes are shorter, and the plants are more rigid.

Plants without zinc form grayish-brown to bronze-colored irregular spots, usually appearing first on leaves halfway up the plant, but sometimes on the older or on the younger leaves, and finally on almost all the leaves. The affected tissue becomes sunken and finally dies. Badly diseased plants have brownish-colored spots on the leaf petioles and stem. Plants grown without zinc are significantly shorter than normal and they have a smaller weight of foliage and tubers.

On acid soils enough zinc goes into the soil solution to prevent the appearance of zinc-deficiency symptoms in the potato. It is possible that a deficiency might occur on highly calcareous soils or on those heavily limed. To correct zinc deficiency in other crops, zinc sulfate has been commonly used.

WHEN MORE THAN ONE ELEMENT IS DEFICIENT

Potato plants grown in river sand with both potassium and phosphorus omitted have normal plant shape and color, but the growth of the stems, roots and tubers is strongly checked (26).

With phosphorus and nitrogen omitted, the petioles, leaflets and leaf margins are still more erect than in the case of phosphorus deficiency alone, but the leaves are lighter green in color. The plants are dwarfed and very stiff, the leaflets small, roots and tubers poorly developed.

With potassium and nitrogen omitted, the dark-green color characteristic of potassium deficiency is absent but the interveinal tissue protrudes upward and the leaves and margins of the leaflets are curved downward. The plants remain small and the roots and tubers are poorly developed.

Where all three of these important elements—potassium, phosphorus and nitrogen—are omitted, growth is severely checked, but the shape and color of the plants are close to normal.

At present very little is known concerning the combined influence of a deficiency of two or more minor elements on the potato plant. For example, with both boron and calcium well below the optimum physiological requirements, the growth reactions might be expected to be a blending of the individual effects of the deficiencies of the two elements, or the symptoms of one deficiency might dominate or mask those of the other.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS OF THE POTATO

General characteristics: Reduced growth. More or less localized effects. Parasitic or virus disturbances absent. Change in color of plant.

ELEMENT DEFICIENT

A. Effects general on entire plant or confined to older or lower leaves.

B. General on entire plant; also yellowing and drying up, or "firing," of lower leaves. Acute stages develop reddish to purplish color in lower leaves.

C. Color fades, beginning with tips and margins of leaflets, until all foliage becomes a lighter green than normal. In time color may fade to pale yellow. In extreme cases margins of lower leaves become devoid of chlorophyll and curl, sometimes "firing." Stunted growth and defoliation are characteristic. . . . . Nitrogen

C. Foliage crinkly and dark green. In acute cases lower leaves become purplish. Plants stiffly erect. Petioles, leaflets and leaf margins take an upward direction. Leaflets often cup-shaped. Leaves fail to expand to normal size. Growth seriously affected when deficiency is acute. Tubers may have rust-brown lesions occurring internally. . . . . Phosphorus

B. Localized, occurring as mottling or chlorosis (loss of green color), with or without necrotic (dead) spots on lower leaves; practically no drying up of lower leaves.

C. Lower leaves lighter green than normal. Chlorosis begins at tips and margins of lowermost leaves and progresses between veins toward center of leaflet. Eventually tissue between veins is filled with brown dead areas. A definite bulging between veins and thickening of foliage occur. Affected leaves are brittle. . . . . Magnesium

C. Foliage darker green than normal. Leaf reduced in size. Internodes remain short. Plants have a humped-up, recurved appearance. Foliage becomes crinkled, and veins appear sunken. Later the older leaves become a trifle yellowish. Then a bronzing develops from tips and margins and gradually involves the entire plant. This bronzing is particularly evident in mass effect. In final stage plants are susceptible to attack by parasitic organisms. . . . . Potassium

C. Lower leaves chlorotic, develop grayish-brown to bronze irregular spots, first usually on leaves midway of plant, eventually affecting practically all foliage. Spots become sunken and involved tissue finally dies. In extreme cases internodes remain short and leaves small and thick. Spots develop on petioles and stem, top leaves assume a slightly vertical position, and margins of leaves may curl upward. . . . . Zinc

A. Effects localized on newer leaves of plant.

B. Terminal bud dies, preceded by unusual distortions at the tips or bases of the young leaves making up the terminal bud.

C. The young leaves of the terminal bud are lighter green than normal, the lighter color being most pronounced at the base. Stem tip may die or make distorted growth. Internodes remain shortened, giving plant a bushy appearance. Leaves become thickened and roll upward, and leafstalks become brittle. Anthocyanin (purple pigment) may develop. Tips and margins, especially of lower leaflets, die prematurely. Tubers remain small and often have a ruptured surface. . . . . Boron

C. Earliest symptom is a light-green band along margins of young leaflets of terminal bud. Such areas often die (necrosis), giving leaflet

	Element deficient
a crinkled or buckled appearance. In some cases young leaves at top remain folded, causing tip to die. Margins of leaflets often roll upward. Axillary buds may show same symptoms as terminal bud. Tubers develop dead spots in the pith region. These first show as a diffuse brown discoloration within the vascular ring at stem end..........	Calcium
B. Terminal bud remains alive; chlorosis of newer leaves, with or without spots of dead tissue; veins light or dark green.	
C. Young leaves show loss of turgor and remain permanently wilted. Terminal bud tends to droop when flower buds are developing, especially if shortage is marked. Drying of leaflet tips occurs in advanced stage. No pronounced chlorosis develops..........	Copper
C. A slight uniform chlorosis first develops in the young leaves. Tips and margins maintain green color longest. Principal veins retain normal green color. Affected tissue gradually becomes pale yellow. Foliage becomes white in extreme cases. No dead spots in evidence.	Iron
C. Areas lighter green than normal first developed between veins of leaves and in tops of stems. These areas may become yellow to white. Numerous small brown patches develop which in time become more extensive. Lower leaves least affected. Mild shortage causes only slight chlorosis, chiefly confined to upper parts of the stem, and no dead spots develop..........	Manganese
C. Symptoms develop slowly. A general yellowing of the leaves and veins occurs similar to that in nitrogen deficiency without leaves drying up. Growth of the plant is materially checked. Some spotting of the leaves occurs if shortage is acute or prolonged.	Sulfur

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Courtesy of Virginia Truck Experiment Station and Bureau of Plant Industry, Soils and Agricultural Engineering, U. S. Department of Agriculture

Plate I.—Above: The potato plant at the left is normal. The one on the right shows incipient stages of nitrogen deficiency, of which rolling of leaflets and general reduction in size and vigor are predominant symptoms. Below: The leaf at the left is normal. The leaf at the right is from a potato plant growing in soil highly deficient in nitrogen. It is characterized by light-green color in the center of the leaflets and distinct loss of chlorophyll at the margins, with tendency to "fire" and curl at the edges.

Courtesy of U. S. Department of Agriculture

Plate 2.—Potato plants showing phosphorus-deficiency symptoms. Left, critical stage resulting from extremely low phosphorus supply. Terminal growth has stopped; plant did not recover when phosphorus supply was increased. Right, incipient stage showing stunted growth, dark green foliage, and cupping of lower leaves with some tip-burn. This plant recovered when phosphorus supply was increased.

Courtesy of Maine Agricultural Experiment Station

Plate 3.—Left, normal growth of potatoes that received 2,000 pounds of 4-8-8 fertilizer. Right, potatoes showing phosphorus-deficiency symptoms; they received the same amounts of nitrogen and potash, but no phosphoric acid. These plants are darker green in color and stunted in growth, the foliage is crinkly, and the leaflets fail to expand normally. Growth continues beyond the normal time of maturity.

Courtesy of Virginia Truck Experiment Station

Plate 4.—A deficiency of potassium in the potato plant retards growth and reduces the size of leaves, which lose their smooth surface, becoming crinkled and curved downward. In the early stage the plant takes on a dark-green color. Later the leaves develop a characteristic bronzing and yellowing, which, starting from the tip and edge, gradually involves the entire leaf.

Courtesy of Virginia Truck Experiment Station and Bureau of Plant Industry, Soils and Agricultural Engineering, U. S. Department of Agriculture

Plate 5.—Magnesium deficiency as it affects the potato. Four stages, including (1) normal leaf; (2) first symptom at tip of terminal leaflet; (3 and 4) advancing stages. Loss of color and "firing" of foliage are prominent symptoms. Foliage is characteristically brittle in advanced stages.

Courtesy of J. A. Chucka and S. M. Raleigh, Maine Agricultural Experiment Station

Plate 6.—Calcium deficiency (right) produces a light-green band along the margins of the young leaves of the potato plant and causes the terminal bud to cease to function, giving a rosetted effect. In serious cases the terminal bud dies and subsequent growth is from the sides. Normal plant at left.

Courtesy of J. W. Shive, New Jersey Agricultural Experiment Station

Plate 7.—Right, potato plant lacking boron in its diet. Leaves thicken and the margins roll upward. The main characteristic is death of the terminal bud. Some chlorosis develops, and petioles become brittle. Leaf points and margins die prematurely. Left, terminal growth of this plant was completely arrested by boron deficiency.

Courtesy of J. W. Shive, New Jersey Agricultural Experiment Station

Plate 8.—Normal potato plant at the right. The plant at the left did not receive manganese, and the results of the deficiency are clearly shown. Light-green color developing in the interveinal tissue is the first symptom.

Courtesy of J. W. Shive, New Jersey Agricultural Experiment Station

Plate 9.—The final stage of manganese deficiency is shown in the potato leaf on the left, which is practically devoid of chlorophyll. Normal potato leaf on right.

CHAPTER V

Plant-Nutrient Deficiency Symptoms in Cotton

By H. P. Cooper and Leroy Donald [1]

THE climatic conditions and soil materials existing in the Southeastern States have resulted in the development of soil complexes which give marked responses to applications of fertilizer. This has been an important determining factor in the many changes and drastic readjustments that have occurred in the agricultural pattern of the southeastern region. The virgin soils were capable of supporting a more or less diversified, self-sufficient type of agriculture. As long as suitable virgin land was available for clearing, the farm soils were abandoned when they became depleted and were allowed to return to trees. The lack of any more available areas of virgin soil finally forced farmers to use more chemical fertilizers. In addition to adjusting agriculture to depleted soils, it was necessary to meet the competition of other agricultural regions and also to develop a satisfactory economic and social system.

The agricultural systems in the Southeast during various periods have depended primarily on a single cash crop suitable for cultivation on an extensive scale and with relatively high value per acre—such as tobacco, rice or cotton—or a small number of such crops at one time. This in itself has tended to bring about serious depletion of soil resources and to increase the necessity for using chemical fertilizers. The cash crops used, in turn, had to produce sufficient income to purchase the fertilizer necessary to maintain the productivity of the soil. The use of relatively large amounts of chemical fertilizers on crops of high acreage value is widespread and is undoubtedly a sound economic practice. Large quantities may be used before reaching the point of diminishing returns.

The six Southeastern States from North Carolina to Mississippi have used approximately 50 percent of the fertilizer consumed in the United States. The cotton crop receives a very large proportion of this fertilizer. Prior to 1930, approximately 30 percent of the total tonnage of fertilizers used in the United States was used in the production of cotton. Reduction in the cotton acreage during the following decade decreased the amount to about 20 percent of the total tonnage. In more recent years, a further decrease has occurred

[1] H. P. Cooper is dean of the School of Agriculture, Clemson Agricultural College, and director of the South Carolina Agricultural Experiment Station; and Leroy Donald is chief agronomist of the Lion Oil Company.

with the result that only about 10 percent of the fertilizer consumed domestically today is being applied on cotton. No doubt this last and rather substantial reduction in percentage of the total tonnage of fertilizers used on cotton can be attributed to the expanded use of fertilizers on food and feed crops resulting from the impetus of war. Cotton is today in fourth-place position, being preceded by corn, small grains and vegetables in the order mentioned.

The use of complete fertilizers is more general in the southeastern than in the western section of the Cotton Belt. The better alluvial delta soils such as in the Red and Mississippi river valleys usually receive only nitrogen in the fertilizer program. Good response is usually obtained, however, from applications of both nitrogen and minerals on upland soils generally, as well as on bottom land soils adjacent to the smaller streams.

RESPONSES OF COTTON TO FERTILIZERS

Botanically, cotton is a perennial plant, but it is grown as an annual crop in the main cotton-producing sections of this country. The plant has an indefinite growth period and is considered a long-season crop. Thus it is possible to study the appearance and extent of deficiency symptoms over a considerable period.

The deficiency symptoms usually described in the cotton plant are those commonly corrected by the addition of certain fertilizer materials. Growth response is usually attributed to a particular nutrient added to the soil. However, as most of the fertilizers ordinarily used contain a large number of nutrients as impurities, it is difficult to distinguish their effects clearly. Since there has been only a very limited amount of carefully controlled experimental work with nutrient cultures in the case of cotton, it may not be possible to state definitely that a particular symptom in the cotton plant results from the lack of a particular nutrient. Investigators may differ widely in their interpretation of the cause of a certain symptom. Because of the limitations of the experimental information available, it seems best at present to relate the deficiency symptoms observed in cotton to the fertilizer materials that correct them rather than to single elements.

It is also often impossible to differentiate between symptoms resulting from a lack of available nutrients in the soil and those due to diseases and insect pests. Even when there is an abundance of available nutrients, their absorption or utilization may be affected by injuries to plants caused by diseases or insects, and deficiency

symptoms may appear. Such situations may lead to much confusion in interpreting experimental results unless all the factors involved are carefully considered.

Deficiencies of potassium and possibly of sulfur are most likely to occur during relatively dry growing seasons, whereas deficiencies of magnesium and manganese are more frequent during relatively wet growing seasons. Some important potassium and sulfur compounds are only slightly soluble in the soil solution, and there may not be sufficient amounts of these nutrients available when the season is dry. Certain magnesium and manganese compounds, on the other hand, are highly soluble and may be readily leached from the soil. This is true, for example, of magnesium nitrate, magnesium chloride, and magnesium sulfate. Magnesium-deficiency symptoms are particularly likely to occur in wet seasons if large amounts of nitrates, chlorides or sulfates have been added to the soil in fertilizers.

The soil reaction also may be an important factor. The solubility of potassium, manganese, iron and boron may be decreased by the addition of large amounts of liming material to the soil to decrease acidity. The strongly acid, highly leached, gray sandy loam soils of the South Atlantic Coastal Plain are often very low in manganese, iron and boron, and the availability of these nutrients may be reduced by the use of lime, resulting in deficiency symptoms in the plants.

The rate of growth of cotton may be another important factor in nutrient deficiencies. With slow growth, soil nutrients may dissolve fast enough to meet the needs of the plants and prevent marked deficiencies. Slow-growing plants in pot cultures in the greenhouse in winter may not show deficiency symptoms, whereas plants grown on the same soil in the field may show marked symptoms. Yield per acre has a similar effect. The rate at which nutrients become available may be adequate for small yields. This is very often true with potash. Where the yields are low, there may be little response from the use of potash in the fertilizer, but where they are high, the response may be marked.

THE SIGNIFICANCE OF SOLUBILITY OF CERTAIN NUTRIENT COMPOUNDS

The chemical composition of plants is such that the strength of ions may be of greater significance in determining the absorption of nutrients than is the concentration of ions (6-14).[2] However, since

[2] All of the selected references are not cited in the body of the text. Only those dealing with specific aspects of the nutrition of cotton are cited.

the concentration of the different ions in the solution may affect the intensity of nutrients absorbed by plants, consideration should be given to the relative solubility of different nutrient compounds.

The data in table 1, reported by Hodgman (20), show a wide variation in the solubility of the common nutrient compounds. The low solubility of many of the calcium compounds may be a reason why many of our high calcium soils are classified as among the most productive. With the exception of calcium nitrate and calcium chloride, practically all calcium compounds are rather insoluble, and

TABLE 1.—SOLUBILITY* OF CERTAIN NUTRIENT COMPOUNDS IN GRAMS OF ANHYDRIDE PER 100 GM. COLD WATER TEMPERATURE AROUND 30° OR 0°C., AS INDICATED

Ion	HCO_3	CO_3	C_2O_4	OH	SiO_2	PO_4	HPO_4	H_2PO_4	SO_4	NO_3	Cl
K.....	22.4	112.0	33.0	97.0°	s.	sl.s.	v.s.	33.0	12.0	31.6	34.7
Na....	6.9°	7.1°	3.7	109.0	s.	28.3	21.9	110.3	19.5°	73.0°	35.7°
NH_4...	11.9°	100.0	4.0	42.0	....	....	42.9°	22.7°	70.60°	118.3°	29.7°
Ca.....	......	0.0014	0.00067	0.185°	0.0095	0.002	0.02	1.8	0.298	102.0°	59.5°
Mg....	......	0.0106	0.07	0.0009	....	0.02	0.31	....	26.0°	42.33	35.3
Al.....	......	....	i	0.00015^{20}	sl.s.	i	....	....	31.3	63.7	69.9^{15}
Mn....	......	0.0065	0.03	0.0002	i	....	....	....	52.0	426.4°	62.2
Zn.....	......	0.001	0.00079	0.0000026	i	i	i	i	86.5^{80}	327.3^{10}	432.0
Fe.....	......	0.0067	0.022	0.00067	....	....	....	....	15.65	83.5	64.4
Co.....	......	i	i	0.00032	....	i	....	....	36.2	133.8°	45.0^{7}
Cu....	......	i	0.0025	i	....	i	i	i	14.3°	137.8°	70.6°

*s=soluble, v=very, sl=slightly, i=insoluble.

this insolubility is responsible for accumulation of many insoluble calcium compounds in the soil. The high calcium content in the cotton plant indicates that an adequate supply of available calcium in the soil is needed to secure maximum yield responses from fertilizer applied to this crop.

Likewise, the high solubility of potassium and sodium carbonates indicates a need for adequate potassium or for a combination of potassium and sodium which will help maintain a supply of carbon dioxide for the synthesis of the highly carbonaceous cotton crop. The solubility values suggest that some of the micro-metallic nutrients must be present in the soil in such compounds as sulfates, chlorides and nitrates in order to be readily available to many plants.

THE WIDE SOIL ADAPTATION OF THE COTTON PLANT

The cotton plant has a wide climatic adaptation ranging from tropical to temperate climates, and it is grown successfully over a very wide range of soil conditions.

The cotton plant is highly tolerant to dry-climate, alkali pedocal

soils (whose profile contains a zone of calcium carbonate accumulation) and to humid-climate, highly acid pedalfer soils (showing no accumulation of calcium carbonate). The wheat plant is the only other major staple crop plant with a comparable or a wider climatic and soil adaptation. The cotton plant apparently has a high capacity to synthesize organic-acid compounds, providing a possible mechanism to account for the absorption of a relatively large quantity of mineral nutrients. The capacity of the plant to synthesize organic-acid materials would make possible a wide variation in the mineralogical composition of a plant making satisfactory growth and production. Some experimental information reported by Cooper and Garman (8) suggests that the ratio of alkaline earth to the alkali-nutrient elements influences the relative vegetative growth and the fruiting habits of the cotton plants. Adequate to excessive quantities of calcium in the nutrient medium apparently tend to lower the relative vegetative growth and stimulate early and abundant fruiting. The nutrient-deficiency symptoms are likely to be pronounced on heavily fruited plants.

Since the mineral composition of the cotton plant is not as definitely fixed as that of some other plants, it should be carefully studied.

CHEMICAL COMPOSITION OF THE COTTON PLANT

In considering the nutrient-deficiency symptoms of plants it is highly desirable to know something about the chemical composition of the crop. It is generally recognized that some plants selectively accumulate certain nutrients. The data on the average chemical composition of 28 samples of cotton plants and 8 samples of cotton seed, representing a wide variety of the soil conditions found in South Carolina, are included in table 2. The elements are arranged according to the relative strength of ions as measured by electrode potentials or discharge potentials of acids on platinum electrodes.

The content of the different elements indicates that cotton is a calcium-accumulating plant. Only a relatively small quantity of silicon is absorbed by the cotton plant under the conditions prevailing in this region (6 to 14). Such calcium-accumulating plants apparently possess the capacity to synthesize organic-acid complexes capable of forming low solubility calcium compounds in the plant. Such characteristics probably result in a fairly constant calcium content in plants. Since some of the soils in the native habitat of the cotton plant may have contained a soil horizon of calcium

TABLE 2.—COMPARATIVE AVERAGE CHEMICAL COMPOSITION OF 28 COTTON PLANTS AND 8 COTTON SEED SAMPLES

The elements are arranged according to relative strength of ions as expressed in standard electrode potentials or discharge potentials of acids on platinum electrodes.

Material	*Ion*	*Normal Electrode Potentials in Volts*	*Percent Dry Matter*		*Percent of K Values*	
			Plant	*Seed*	*Plant*	*Seed*
Potassium	K^+	+2.92	0.830	0.129	100.00	100.00
Sodium	Na^+	+2.71	0.450	0.012	54.22	1.06
Calcium	Ca^{++}	+2.50	1.700	0.077	204.82	6.82
Magnesium	Mg^{++}	+1.55	0.453	0.365	54.58	32.33
Aluminum	Al^{+++}	+1.30	0.040	0.006	4.82	0.53
Manganese	Mn^{++}	+1.10	0.030	0.001	3.61	0.09
Iron	Fe^{++}	+0.43	0.056	0.007	6.75	0.62
Silicon	....	....	0.093	0.011	11.20	0.97
Sulfur	HSO_4^-	−1.69*	0.280	0.565	33.73	50.04
Phosphorus	$H_2PO_4^-$	−1.70*	0.240	0.684	28.92	60.58
Chlorine	Cl^-	−1.36	0.750	0.036	90.36	3.19
Nitrogen	NO_3^-	−1.69*	1.910	4.040	230.12	357.84

* Discharge potentials on platinum electrodes.

carbonate accumulation, it is logical to expect that the cotton plant would possess the capacity to tolerate fairly high concentrations of calcium ions. The nitrogen, potassium, chlorine, magnesium and sodium content of the cotton plant is relatively high. The high nutrient content of the cotton plant suggests the desirability of adding liberal quantities of a complete fertilizer to many of the soils used for the production of cotton. The relatively high content of nitrogen, phosphorus and sulfur in the seed indicates the need for a liberal available supply of these nutrients in the production of high-quality cotton seed.

EFFECTS OF NITROGEN ON THE GENERAL GROWTH BEHAVIOR OF COTTON

The framework of a cotton plant normally consists of a monopodial main axis with lateral branches arising from the leaf axils. There are two buds in each of the leaf axils, according to Wadleigh, one of which is a true axillary bud that can give rise to a vegetative secondary axis. The other is an extra axillary or lateral bud out of which may develop a sympodial fruiting branch. The growth of the main axis, and thus the extent to which progressive development of lateral vegetative and fruiting branches occurs, as shown by Wadleigh, is conditioned by the nutritional status of the plant. His data

indicate that the nitrogen level limits not only the height of the cotton plant but also the number and length of both vegetative and fruiting branches and, hence, the number of leaves and fruiting forms which finally develop.

Symptoms of nitrogen deficiency manifested themselves early, as frequently observed, in the low-nitrogen plants studied by Wadleigh. He described the plants as being stunted, with light-green leaves, the blades and petioles of which were reduced in size. By contrast, the leaves of plants supplied with adequate nitrogen were larger and deep green in color. True intermediates between these extremes were realized from each successive increment of nitrogen applied. The marked increase in the green and dry weight of plant tops with each increment of nitrogen, as determined by Wadleigh, reflects this difference in foliage development. A similar difference in size and intensity of color has frequently been observed even in the cotyledonous or seed leaves which make their appearance well in advance of the true leaves.

Long before initiation of reproductive activity by cotton plants grown under low levels of nitrogen, Wadleigh detected a lower proportion of total nitrogen in their leaves with an approximate corresponding increase in the proportion of this component in the fruiting branches. Such a relationship is to be expected when nitrogen is limited, as he explained, since it is the inherent tendency for plants to supply reproductive organs at the expense of vegetative parts. Since nitrogen is a key component of the green pigment or chlorophyll, the color of the leaf grows less intense as the translocation of nitrogen reserves to the fruiting forms increases. As the chlorophyll disappears, the yellow pigments normally masked by the green become visible and increasingly evident. Disorganization of the plant cells which follows is often accompanied by a development of red pigments known as anthocyanins. Eventually the leaf turns brown and dies, and finally it falls to the ground. The commonly observed early change in color within the leaves and succulent stems of cotton from green to yellow, to variously tinted shades of red, and finally to brown is thereby explained. This premature discoloration and eventual shedding of leaves is, therefore, directly attributable to an inadequate level of nitrogen within the cotton plant.

Under the conditions of his experiment, Wadleigh found that plants highly deficient in nitrogen failed to produce any lateral vegetative branches. On the other hand, from two to five vegetative branches developed on those plants to which he had supplied ade-

quate nitrogen. The mechanism was thereby provided for vastly accelerated photosynthetic activity, and thus greatly increased carbohydrate production.

Incident to his investigations, Wadleigh found that plants low in nitrogen produced as an average only 12 fruiting branches. In marked contrast, an average of 23 fruiting branches developed on those plants receiving adequate nitrogen. It is thus evident that the magnitude of the fruiting zone of a cotton plant has a definite relation to nitrogen supply when other conditions are not limiting.

In discussing the development of a fruiting branch, Wadleigh pointed out that a flower bud, which in reality is a terminal bud, normally occurs at each node of a fruiting branch. Further elongation of the fruiting branch arises from a lateral bud. Therefore, flowering starts on a cotton plant at the primary nodes of the lowermost fruiting branches and continues centrifugally and acropetally. Depending on the limitation in nitrogen reserves, the probability of each successive bloom setting and developing is lowered by the nutritional demands of the one originally initiated. Lack of nitrogen nutrition was found by Wadleigh to limit both the total number of flowers produced and the extent to which they may occur and develop on the outer nodes of a fruiting branch.

Fruiting charts prepared by Wadleigh reveal that when low-nitrogen plants had produced about 20 blossoms as an average, with practically no flowers appearing beyond the third node, all other young squares dropped. Early abortion of terminal buds of fruiting branches followed closely which definitely curbed initiation of additional squares. Furthermore, when the low-nitrogen plants had set about five bolls as an average, all other young bolls fell off. Plants grown at the highest level of nitrogen studied in his experiment, however, produced nearly three times as many blossoms and set more than four times as many bolls. Wadleigh further found that 90 percent of the bolls which did set on plants highly deficient in nitrogen occurred at the primary nodes, whereas only 50 percent were so located on plants which had received adequate nitrogen.

It thus appears that the abscission process in the cotton plant acts as a "safety valve," in that all fruiting forms are shed which cannot be adequately developed at the obtaining level of metabolism of the plant. It is interesting to note in Wadleigh's data, however, that 60 to 70 percent of all blossoms produced by cotton plants, regardless of the level of nitrogen nutrition studied, are shed. This

is consistent with the usual observation that cotton naturally produces many more flowers than it can mature into fruit.

Wadleigh also found that nitrogen nutrition exerts a determinative effect as to which fruiting branches bear the major portion of the flowers and set bolls. He determined that 70 percent of the bolls set on nitrogen-deficient plants were carried on the first five fruiting branches which bore 98 percent of the blossoms. In effect, the nitrogen-deficient plants produced only a "bottom" crop of bolls. On bolstering the nitrogenous reserve of the plant, however, an increasing productiveness of the upper branches resulted. Some bolls, for instance, were set above the twentieth fruiting branch of plants supplied with adequate nitrogen, which resulted in the production of a "top," "middle" and "bottom" crop of bolls. In the light of these investigations, Wadleigh stated that fruiting behavior in the cotton plant is definitely a function of the amount and quality of food reserves rather than of water supply to which some investigators have attributed the shedding of fruiting forms.

The further deduction may be made from Wadleigh's results that there is no significant difference in the number of seeds initiated in bolls of plants low or high in nitrogen. In plants deprived of adequate nitrogen, however, a marked decrease in the number of seeds which developed per boll, with a resulting increase in the number of motes or aborted embryos, occurred as the fruiting season progressed. The trend was converse in plants which received adequate nitrogen. Embryo abortion obviously limits weight of seeds and hence conditions boll size. Wadleigh thus reported that nitrogen nutrition tended to increase boll size.

Wadleigh also found that the average weight of the individual seeds tended to increase with an increase in level of nitrogen nutrition, accompanied by a marked increase in protein content. Seeds produced by low-nitrogen plants were found to be only 17.6 percent protein, whereas seeds from high-nitrogen plants contained 27.0 percent protein. The oil content, as determined by Wadleigh, was 29.2 percent in seed from plants inadequately supplied with nitrogen as compared to 24.1 percent in seed from plants receiving adequate nitrogen. An increase in both number and size of bolls resulting from adequate nitrogen, however, should result in more total oil being produced per acre.

The lint percentage, according to Wadleigh's observations, tended to decrease with an increase in nitrogen supply to the plants. He ascertained by several different criteria of measurement, however,

that the length of the lint showed a slight trend to increase with an increase in the level of nitrogen.

The aforementioned findings led Wadleigh to conclude that a definite relationship exists between growth of cotton plants, as indicated by vegetative vigor, and yield of lint and seed. This expected relationship, he further concluded, is frequently disturbed by the ravages of insects and diseases. Yet the fact remains that small, stunted plants cannot produce a bumper crop.

Based on the foregoing facts established through research conducted by Wadleigh and other investigators, as well as frequent field observations which corroborate their findings, the readily discernible symptoms of nitrogen deficiency in cotton may be summarized as follows:

1. Young leaves pale, yellowish green in color, fading with age first to hues of yellow, then often to variously tinted shades of red, and finally to brown as they dry up and are prematurely shed.
2. Individual leaves reduced in both number and size of blade and petiole, as well as intensity of color.
3. Plants short and stunted, resulting from an early termination in growth of the main axis or primary stem.
4. A scarcity or complete absence of lateral vegetative branches.
5. Fruiting branches few and short, resulting from cessation of apical growth which usually follows the setting of their first bolls.
6. Flowers reduced in number, followed by a sparse setting of bolls confined usually to the first nodes of the lowermost fruiting branches.

DEFICIENCY SYMPTOMS IN COTTON

The capacity of the plant to accumulate calcium, to synthesize acid-organic compounds and to develop an extensive tap-root system may partially account for the lack of widespread deficiencies of metallic micronutrients. This intensifies the requirement for alkali metals, such as potassium and sodium, or ammonium, and enables the plant to maintain a supply of available carbonate ions necessary in the production of a high-yielding carbonaceous fiber crop.

Deficiency symptoms in cotton will be described in the succeeding pages. A brief key to symptoms is given at the end of the chapter. In both the descriptions of symptoms and the key, the limitations already described should be kept in mind. Following the descriptions of symptoms, some important aspects of the relationship of soil characteristics and plant composition to nutritional deficiencies and the fertilizer needs of the cotton plant will be discussed.

Nitrogen

Nitrogen-deficiency symptoms in cotton are characterized by relatively meager growth and yellowish-green color of foliage. The older leaves are the most severely affected, as is shown by the fact that the lower leaves dry up and are prematurely shed. The typical growth response of cotton to an application of 600 pounds per acre

Courtesy of Alabama Agricultural Experiment Station

Figure 1.—Normal cotton plant showing growth produced when fertilized with 600 pounds of 6-10-4 per acre.

of a 6-10-4 fertilizer on Hartsells sandy loam at the Sand Mountain Agricultural Experiment Station in Alabama is shown in figure 1. Figure 2 shows a plant suffering from nitrogen deficiency, grown in soil to which was added 600 pounds per acre of 0-10-4 fertilizer (no nitrogen).

Courtesy of Alabama Agricultural Experiment Station

Figure 2.—Effect of nitrogen deficiency on growth of cotton. This small, yellowish-green plant was grown on a plot receiving 600 pounds per acre of 0-10-4 fertilizer.

The yellowish green leaf color resulting from a deficiency of nitrogen is illustrated in plate 1, page 165.

Most of the cotton soils in the Southeastern States are relatively low in nitrogen, and it is necessary to utilize fertilizer nitrogen to secure optimum production. It is a common custom to make two applications of nitrogen to the cotton crop. A complete fertilizer containing 3 to 5 percent of nitrogen is applied before or at the time of planting and a side application of nitrogen is added about the time of the first cultivation. Such a program requires more labor in applying the nitrogen, but it prevents the possibility of a large loss of soluble nitrogen in the drainage water. The two applications of nitrogen provide a more uniform supply of available nitrogen to the plant and tend to reduce the intensity of the nitrogen-deficiency symptoms.

Phosphorus

Phosphorus is usually the limiting nutrient in virgin cotton soils of humid climates. The symptoms of phosphorus deficiency in cotton are not so pronounced as those caused by a lack of nitrogen. The most outstanding are a dark-green color of the foliage and a generally dwarfed type of plant. The dwarfed plant shown in figure 3 was grown at the Sand Mountain Station on Hartsells sandy loam to which 600 pounds per acre of 6-0-4 fertilizer were added. The dark-green color of an individual leaf is illustrated in plate 1 and in plate 3, pages 165, 166. Figure 4 shows the field condition of phosphorus-deficient plants grown in Orangeburg fine sandy loam at the South Carolina Agricultural Experiment Station. It is clear from figure 4 that a deficiency of phosphorus results in delayed fruiting and maturity—a very serious problem where boll-weevil damage is likely to be heavy.

Phosphorus is applied to most of the upland soils in the Southeastern States. The relatively low pH value in many of the soils

indicates soil complexes most likely to lock up large quantities of phosphorus in insoluble compounds, and significantly decreases the availability to plants of added phosphorus. At favorable pH values for optimum growth of cotton the added phosphorus is likely to remain in more readily available combinations. The greater efficiency in the use of phosphorus at favorable soil pH value may significantly lower the degree of the phosphorus-deficiency symptoms in cotton grown on soils relatively low in available phosphorus. The calcium content of the superphosphate commonly utilized in cotton fertilizer may be an important constituent in determining the growth and production of the plant.

Courtesy of Alabama Agricultural Experiment Station
Figure 3.—Effect of phosphorus deficiency on growth of cotton. This small dark-green plant was grown on a plot receiving 600 pounds per acre of a 6-0-4 fertilizer.

Figure 4.—Effect of phosphorus deficiency on maturity of cotton. Plot at left received 4-0-4 fertilizer and shows typical late maturity. Plot at right received 4-8-2 fertilizer.

Potassium

The capacity of the cotton plant to accumulate calcium and synthesize organic-acid compounds may tend to buffer or lower the degree of absorption of carbon dioxide and very probably tends to intensify the need for potassium to maintain an adequate supply of soluble carbonate ions. These ions are necessary in the synthesis of constituents required in the production of cotton fibers.

Figure 5.—Cotton showing potassium-deficiency symptoms. Plot at right received no potash. The leaves shed prematurely and the bolls are dwarfed. Plot at left received a complete fertilizer.

The symptoms in cotton associated with a lack of potash (potassium) in the fertilizer may be very pronounced. The problem has been given much study. A lack of potassium often results in a striking malnutritional symptom commonly called "cotton rust" or "potash hunger." Typical symptoms in the cotton leaf are illustrated in plate 4, page 167. The first symptom in the leaf is a yellowish-white mottling. The leaf changes to light yellowish green, and yellow spots appear between the veins. The centers of these spots die, and numerous brown specks occur at the tip, around the margin, and between the veins. The tip and the margin of the leaf break down first and curl downward. As the physiological breakdown progresses, the whole leaf finally becomes reddish brown in color, dries, and is shed prematurely. The premature shedding of leaves prevents the proper development of bolls, which are dwarfed

and immature. Figure 5 and plates 5 and 6, pages 167, 168, illustrate both leaf and boll conditions in plants grown on Orangeburg fine sandy loam soil at the South Carolina Experiment Station. Many of the bolls fail to open and the fiber is of poor quality.

Potash-deficiency symptoms are most likely to occur on heavily fruited plants with limited vegetative growth produced on soils with an abundant supply of calcium. The data in tables 3 and 4 show that there is a definite interrelation among potassium, sodium and calcium in the nutrition of plants. The addition of sodium to the nutrient medium seems partially to alleviate the potash deficiency symptoms. The addition of sodium to fertilizer in soils low in potassium significantly increases the yield of cotton.

The increased use of limestone in the Southeastern States has very probably significantly increased the intensity of the potash-deficiency symptoms in cotton. This may be partially due to the lowering of the availability of the soil potassium through the formation of low solubility compounds, and partially due to the increased quantity of calcium absorbed which increases the requirement of potassium for optimum production. Because of the high solubility of potassium tetraborate, the use of potash fertilizers may increase the availability of boron in soil to which calcium carbonate has been added.

Sodium

There are no specific sodium-deficiency symptoms for field-grown cotton plants. It is well known that sodium in a nutrient medium relatively low in available potassium will significantly increase the yield of cotton. The capacity of the cotton plant to utilize sodium probably accounts in part for the increase in yields secured from the use of fertilizers containing this element. The growth response from applying to the soil the equivalent of approximately 100 pounds of sodium oxide on Norfolk loamy sand at the South Carolina Sandhill Experiment Station is illustrated in figure 6. Where no potash was applied in the fertilizer there was a significant growth response from the sodium. The effect of sodium included in a fertilizer on the yield of seed cotton is shown in table 3. Where no potassium was applied there was a 70 percent increase in seed cotton yields from the addition of sodium. With increasing quantities of potash there was a decrease in the response to additions of sodium; with the 60-pound application of potash there was only a 15 percent increase in the yield of seed cotton from the addition of sodium.

The milliequivalent content of calcium, potassium and sodium in cotton plants is included in table 4. There was a fairly constant total cation content at the different levels of potash applications. The addition of sodium had very little influence upon the potassium

SODIUM APPLIED NO SODIUM

Figure 6.—Growth response of the cotton plant to sodium from sodium nitrate as the source of nitrogen in a 600-pound-per-acre application of a 7.5-10-0 fertilizer analysis. Plot on the left received sodium and plot on the right did not receive sodium in the fertilizer.

TABLE 3.—TEN YEARS' AVERAGE INCREASE IN YIELDS IN POUNDS OF SEED COTTON PER ACRE FROM THE ADDITIONS OF SODIUM IN THE FORM OF SODIUM NITRATE

All plats received the equivalent of 600 pounds per acre of 7.5–10–0 fertilizer in addition to the potassium and sodium combinations which contained the equivalent of 100 pounds per acre of sodium oxide.

Pounds of potash per acre, with and without sodium	*Yields of seed cotton, pounds per acre*	*Increase for sodium*		*Increase in yield over plot not receiving potassium or sodium*	
		Pounds	*Percent*	*Pounds*	*Percent*
No potash:					
No sodium	306	....	....	....	....
Sodium	521	215	70	215	70
15 pounds potash:					
No sodium	742	....	....	436	143
Sodium	943	201	27	637	208
45 pounds potash:					
No sodium	1,093	....	....	787	257
Sodium	1,280	187	17	974	318
60 pounds potash:					
No sodium	1,201	....	....	895	293
Sodium	1,383	182	15	1,077	352

TABLE 4.—THREE YEARS' AVERAGE MILLIEQUIVALENT CONTENT OF CALCIUM, POTASSIUM AND SODIUM PER 100 GRAMS OF AIR-DRIED COTTON-PLANT MATERIAL GROWN AT DIFFERENT LEVELS OF POTASH FERTILIZATION ON PLATS RECEIVING EITHER SODIUM NITRATE OR AMMONIUM NITRATE WITH LIME AS A SOURCE OF NITROGEN

All plats received the equivalent of 600 pounds per acre of 7.5–10–0 fertilizer in addition to the potassium and sodium combinations which contained the equivalent of 100 pounds of sodium oxide per acre.

Treatment	*Three-Year Average M. E. per 100 Grams of Plant Material*					*Ave. M. E. Ratio Ca/K+Na*
	Calcium	*Potassium*	*Sodium*	*% Increase in Sodium*	*Total*	
No potash:						
Ammonium nitrate with lime	70.00	19.63	1.42	....	91.05	3.32
Sodium nitrate	60.00	17.43	11.27	694	88.70	2.09
15 pounds potash:						
Ammonium nitrate with lime	74.67	22.47	1.12	....	98.26	3.16
Sodium nitrate	64.50	21.97	11.01	883	97.48	1.96
45 pounds potash:						
Ammonium nitrate with lime	76.33	31.00	1.29	....	108.62	2.36
Sodium nitrate	60.83	32.57	10.75	733	104.15	1.40
60 pounds potash:						
Ammonium nitrate with lime	74.83	35.57	1.69	....	112.09	2.01
Sodium nitrate	57.67	36.73	9.65	471	104.05	1.24

absorbed, but there was a significant reduction in the calcium content of the plant. The effect of sodium on the production of cotton should be considered in connection with the relative quantities of calcium and potassium available to plants. The ratio of calcium to potassium plus sodium should not be greater than one to two for optimum production under the conditions of these experiments.

According to solubility values, potassium should be much more efficient than sodium in maintaining a soluble supply of carbonates available for photosynthesis. Large increases in the production of cotton from the additions of sodium would be expected only on soils deficient in potassium.

Calcium

There are no specific calcium-deficiency symptoms for field-grown cotton plants. However, it is evident that the available supply of calcium in the soil has a very significant effect upon the vegetative growth and fruiting habits of the crop. A low supply of calcium may result in the production of relatively large plants and comparatively few fruit buds. In comparison, an abundant supply of calcium may result in the production of a relatively small plant and stimulate early and abundant fruiting. Three-week-old cotton seedling plants showing calcium deficiency symptoms are illustrated in figure 7. These plants were grown in a complete nutrient solution containing 8 parts per million of calcium. Note the bending of the petioles

Courtesy of John T. Presley, Mississippi Agricultural Experiment Station

Figure 7.—Three weeks old greenhouse seedling cotton plants grown in complete nutrient solution low in calcium (8 p.p.m.). Note the bending and the collapse of the leaf petioles.

and the beginning of the collapse of the entire leaf petiole. These symptoms are also found in the cotyledons and true leaf petioles.

Calcium-deficiency symptoms on older leaf petioles are shown in figure 8. Note the characteristic bending and the collapse of the leaf petioles. These pictures suggest the fate of a large proportion of the seedling cotton plants growing on acid soils low in available calcium, particularly during cool, wet, unfavorable growing seasons.

Courtesy of W. H. Tharp—USDA-BPISAE—Cotton Division

Figure 8.—Calcium deficiency leaf symptoms of 45-day-old cotton plant grown in nutrient solution low in calcium (2.71 p.p.m.). Note the bending and collapse of the affected leaf petioles.

The calcium content of cotton seed is very low. It has been suggested that the intensity of the energy available to seedling plants from respiration may not be sufficient readily to assimilate phosphorus in the form of calcium phosphate. Therefore a large amount of calcium is not accumulated in the seed. However, as soon as the seedling cotton plants emerge from the ground and are capable of utilizing the energy of the sunlight, which contains a higher quality of energy than is commonly available in respiration processes, there is need for an abundant supply of calcium (9 to 14). The loss of a stand from the dying of cotton seedling plants during cool, wet seasons may be definitely related to an inadequate supply of avail-

able calcium. The phylogenetic calcium-tolerance mechanism may result in the synthesizing by seedling plants of organic-acid compounds which have to be partially neutralized to produce the most vigorous growth.

Since the cotton plant is a calcium-accumulator plant, there may be considerable variation in the calcium content of the plant without a significant effect upon growth and yield. As the total quantity of calcium absorbed by the plant may be significantly affected by the capacity of the plant to synthesize organic-acid compounds, there may be a fairly uniform calcium content in plants grown on soils differing widely in calcium content.

The milliequivalent potassium, sodium and calcium contents in the mature cotton plant, shown in table 4, suggest that there is a relation between the ratio of the calcium and the potassium plus the sodium content of the cotton plant. These data suggest that for optimum yields under the conditions of the experiment considered, the calcium should not be more than one to two times the sum of the potassium plus the sodium (8).

Magnesium

The characteristic magnesium-deficiency symptom in cotton is a purplish-red leaf with green veins. Late in the season it is sometimes difficult to distinguish between the color due to magnesium deficiency and that due to aging or maturity, though the latter is apt to be orange red rather than purplish red. Magnesium-deficiency symptoms appear first on the lower leaves as is shown in plate 7, page 169, and figures 9 and 10. The leaves are shed prematurely. This checks the growth of the plant and results in low production. The typical purplish-red leaves and the premature shedding of the foliage are illustrated in plate 8, page 169.

Magnesium-deficiency symptoms in cotton are most frequent in the southeastern part of the United States, including most of the Coastal Plain, some of the Piedmont, the Ozark plateaus, and the southern end of the Appalachian Plateau. The most marked magnesium-deficiency symptoms occur on the strongly leached, highly acid yellow podzolic soils. Magnesium deficiency is much less frequent and serious on the red podzolic soils. The red podzolic soils usually contain considerable quantities of magnesium which may become available to a long-growing-season crop like cotton. The kinds and quantities of fertilizers added to the soil often have a very significant effect upon the occurrence and the extent of mag-

nesium-deficiency symptoms in cotton. This is illustrated in table 5, showing the relation between the magnesium-deficiency symptoms in cotton plants and the source of nitrogen in the fertilizer. The percentage of the red leaves showing magnesium-deficiency symp-

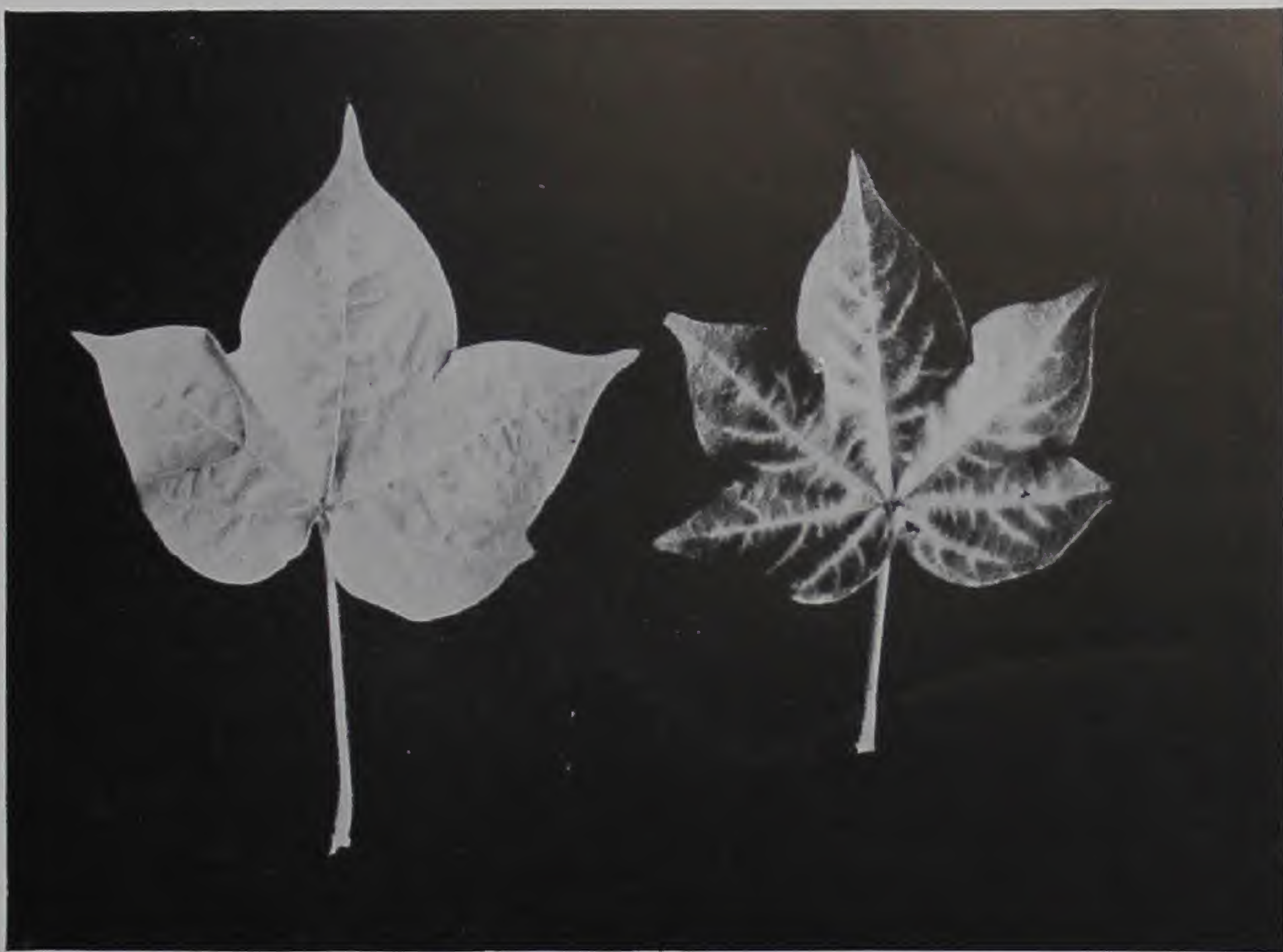

Figure 9.—Magnesium-deficient leaf at right; normal leaf at left.

Courtesy of J. E. McMurtrey, Jr., U. S. Department of Agriculture

Figure 10.—Cotton plants illustrating magnesium-deficiency symptoms. Note that lower leaves are affected first and are shed prematurely.

toms in cotton is very probably related to the solubility of the magnesium compound and the removal of magnesium in the drainage. Where ammonium phosphate was used as the source of nitrogen only 3 percent of the leaves showed magnesium-deficiency symptoms. (See table 5.) This is ascribed to the formation of

TABLE 5.—RELATION BETWEEN MAGNESIUM-DEFICIENCY SYMPTOMS IN COTTON PLANTS AND THE SOURCE OF NITROGEN FERTILIZER ON NORFOLK SAND AT THE SOUTH CAROLINA SANDHILL EXPERIMENT STATION

Source of Nitrogen	*Red Magnesium-Deficient Leaves on Plants August 11*
	Percent
Sodium nitrate	28
Ammonium nitrate plus lime	25
Ammonium sulfate	24
Calcium cyanamide	24
Urea	20
Ammoniated superphosphate	18
Ammonium phosphate	3
Ammonium sulfate plus basic slag	1

magnesium ammonium phosphate, the slight solubility of which prevents the leaching of large quantities of magnesium from the soil.

The occurrence of marked magnesium-deficiency symptoms in cotton has been almost completely eliminated on soils which have received heavy applications of fertilizers containing dolomitic limestone. Critical magnesium-deficiency symptoms would be expected only on soils where large quantities of chloride, nitrate or sulfate ions are present.

MANGANESE

Manganese apparently tends to accumulate in the leaves of plants. In the absence of adequate quantities of this nutrient, the upper or younger leaves are the first to be affected. They become yellowish gray or reddish gray in color with green veins. The characteristic deficiency symptoms observed in solution cultures reported by the New Jersey Agricultural Experiment Station are shown in figure 11. Manganese deficiency is not commonly observed under field conditions except on certain soil types, or where large quantities of liming materials have been added to the soil. The relatively low solubility of manganese hydroxide indicates how the availability of manganese may be significantly lowered through liming.

Courtesy of New Jersey Agricultural Experiment Station

Figure 11.—Right, manganese-deficient leaves. Left, normal leaf.

Manganese-Toxicity Symptoms

The occurrence of crinkle leaf in cotton due to the presence of excessive quantities of water-soluble manganese in the soil has been reported by Neal and Lovett (30, 32). The manganese-toxicity symptoms are reported as follows: The first noticeable feature is the appearance of abnormal leaves. They are puckered, mottled, partially chlorotic and variously distorted in early stages, with necrotic lesions subsequently appearing along and between the

Figure 12.—Crinkle leaf or manganese toxicity of cotton. A, healthy plant. B to D show varying degree of manganese toxicity symptoms. The leaves are puckered, mottled, partially chlorotic and variously distorted.

Courtesy of D. C. Neal—U. S. Department of Agriculture

of zinc in some of the alkaline soils. Under such conditions, the needed zinc can be added most satisfactorily in the form of a spray solution on the leaves of the plants. The relatively high solubility of zinc nitrate, chloride and sulfate suggests that these zinc salts would be the most satisfactory sources of zinc for many plants. The insolubility of zinc phosphates suggests that large quantities of phosphorus in the soil would tend to decrease the availability of zinc to plants.

Sulfur

Sulfur deficiency in cotton is not commonly observed in sections where the ordinary fertilizer materials are applied, since such materials as ammonium sulfate and the common superphosphate contain considerable quantities of this nutrient. The sulfur added to the soil in rainwater and the amount in common fertilizer materials apparently supplies sufficient quantities of sulfur for cotton on most soils. On certain unfertilized soils, or where the fertilizers used contain no sulfur, serious sulfur deficiency may occur in cotton. Sulfur seems to be essential in the formation of chlorophyll, as plants grown in soils with an inadequate supply of this element develop a light-green color. Figure 14 and plate 9, page 170, show the dwarfed growth and yellow color resulting from sulfur deficiency. If sulfur

Courtesy of F. L. Davis, Louisiana Agricultural Experiment Station

Figure 14.—Effect of sulfur deficiency on growth of cotton. The plot on the right received no sulfur in the fertilizer.

veins. As the plant approaches maturity, they become slightly thickened, brittle and ragged at the margins as illustrated in figure 12. The crinkle-leaf symptoms were prevented by increasing the pH value of the soil by an application of lime. More definite information concerning the quantities necessary for optimum growth and toxic amounts of some of the micronutrients is needed. It is very probable that various degrees of manganese toxicity in cotton occur on many of the highly acid red podzolic soils. This condition seems to be readily controlled by the addition of lime.

Zinc

Zinc deficiency in cotton is apparently not very common. Inadequate quantities of this element may result in the leaves becoming extremely chlorotic, with areas of dead tissue. The chlorosis resulting from a deficiency of zinc in water cultures, reported by K. T. Holley, is shown in figure 13. The very low solubility of zinc hydroxide indicates the possibility of lowering the availability of the zinc in certain acid soils through the use of large quantities of agricultural lime. It is very difficult to maintain an available supply

Courtesy of K. T. Holley, Georgia Agricultural Experiment Station

Figure 13.—Cotton leaf showing zinc-deficiency symptoms. Note extreme chlorotic condition and the darker colored veins.

were not present in the fertilizer used in the southeastern section of the Cotton Belt, it is very probable that a marked sulfur deficiency would occur in many cotton fields.

Boron

Boron-deficiency symptoms in the cotton plant first appear in the terminal growth. The terminal buds often die, checking linear growth and producing dwarfed, many-branched plants such as that illustrated in figure 15. The young leaves are yellowish green in

Figure 15.—Right, dwarfed, many-branched cotton plant resulting from boron deficiency. Left, normal plant.

color. At a low boron level, flower buds become chlorotic, the bracts flare open, and the buds drop from the plants.

On heavily limed soils the supply of available boron may be reduced to a very low level and result in the production of cotton plants with few or no buds producing fruit.

In the future a deficiency of boron may occur in many of the soils in the southeastern section of the Cotton Belt. The large increase in the quantity of agricultural lime being applied to cotton soils will significantly decrease the solubility and the availability of boron in the soils. The data in table 6 give the relative solubilities of several boron compounds. The very low solubility of calcium metaborate as compared with the high solubility of potassium tetraborate may be one of the reasons why increasing the

available calcium in the soil decreases the availability of the boron in the soil. Likewise, high solubility of potassium tetraborate suggests that the addition of potassium should increase the availability of the boron in the soil, and some of the increases associated with potash applications may be the result.

Since many of the soils in the southeastern section require an application of lime to produce optimum yields of cotton, an application of boron to the soils requiring heavy applications of limestone may be needed. One of the most satisfactory methods of adding boron to the soil is including borax in the fertilizer. The cost of adding adequate quantities of boron is very low. The main problem is determining the quantity of boron that may be included in the fertilizer without leading to toxicity. It seems probable that boron will become one of the most widespread deficient micronutrients.

TABLE 6.—SOLUBILITY IN GRAMS OF ANHYDRIDE PER 100 GRAMS OF COLD WATER AT DESIGNATED CENTIGRADE TEMPERATURE

Boric acid	$H_3BO_3 = 5.15^{21}$
Potassium tetraborate	$K_2B_4O_7 \cdot 5\ H_2O = 26.70^{30}$
Ammonium tetraborate	$(NH_4)_2B_4O_7 \cdot 4\ H_2O = 7.27^{18}$
Sodium tetraborate	$Na_2B_4O_7 \cdot 10\ H_2O = 1.60^{10}$
Calcium metaborate	$Ca(BO_2)_2 \cdot 2\ H_2O = 0.31^{30}$

PREVENTING NUTRIENT DEFICIENCIES IN COTTON

The occurrence of deficiency symptoms in cotton is more often observed in the regions that use commercial fertilizer in the production of this crop. It is usually possible to eliminate the symptoms at a relatively low cost by including the deficient nutrients in the fertilizer combination.

Suggested rates per acre for the application of various nutrients to prevent serious deficiencies are listed below:

Nitrogen—15 to 50 pounds of nitrogen.
Phosphorus—15 to 50 pounds of phosphoric acid.
Potassium—15 to 50 pounds of potash.
Calcium—add sufficient lime to maintain soil reaction at pH value around 6.00.
Magnesium—10 to 20 pounds of soluble magnesia or 100 to 200 pounds of dolomitic limestone in the row with the fertilizer.
Manganese—25 to 50 pounds of manganese sulfate or the equivalent.
Zinc—20 to 40 pounds of zinc sulfate or the equivalent.
Sulfur—use fertilizer materials containing sulfur.
Boron—5 to 10 pounds of borax or the equivalent.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS OF COTTON

Causal parasites or viruses absent. More or less localized effects and decreased growth.

	Element deficient
A. Effects localized on older or lower leaves or more or less general on whole plant.	
B. Symptoms local, occurring as mottling or chlorosis with or without necrotic spotting (areas of dead tissue) on lower leaves; little or no drying up of lower leaves.	
C. Lower leaves brittle, curved or cupped under, with yellowish-white mottling between veins. Necrotic spots present	Potassium
C. Lower leaves purplish red with green veins	Magnesium
B. Symptoms general, with yellowing and drying, or "firing," of lower leaves.	
C. Plants light green; lower leaves yellow, drying to brownish color	Nitrogen
C. Plants dark green, leaves and plants small, maturity delayed	Phosphorus
A. Effects localized on terminal growth (upper and bud leaves).	
B. Dieback involving terminal buds, resulting in many-branched plant. Young leaves yellowish green, flower buds chlorotic	Boron
B. Terminal buds remain alive; chlorosis of upper or bud leaves.	
C. Leaves yellowish gray or reddish gray with green veins	Manganese
C. Leaves green in color, plant dwarfed	Sulfur

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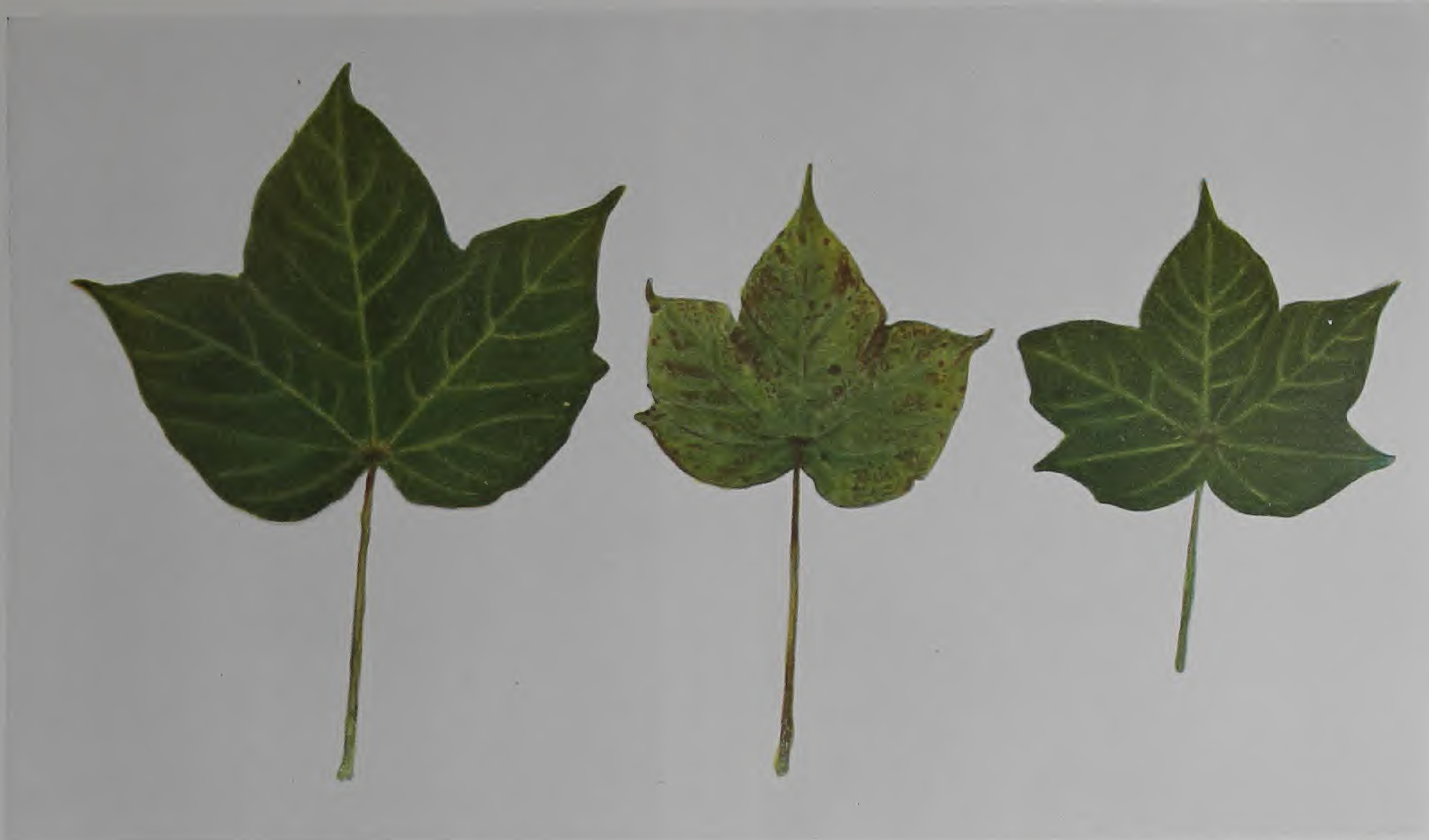


Courtesy of Alabama Agricultural Experiment Station

Plate 1.—Cotton leaves showing normal condition and nitrogen- and phosphorus-deficiency symptoms. Left, normal green color. Center, yellowish-green color due to nitrogen deficiency. Right, dark-green color characteristic of phosphorus deficiency.

Courtesy of Pee Dee Experiment Station, Florence, S. C.

Plate 2.—Nitrogen deficiency in cotton is characterized by yellow color of foliage and slow growth. The plot on the left did not receive nitrogen in the fertilizer; the plot on the right received a complete fertilizer.

Courtesy of Alabama Agricultural Experiment Station

Plate 3.—Effect of phosphorus on color and growth of cotton. Right, the small, dark-green plants exhibiting phosphorus deficiency received a 6-0-4 fertilizer. Left, normal green plants that received a 6-10-4 fertilizer.

Plate 4.—Cotton leaves showing potassium-deficiency symptoms. Left, normal green leaf. Right, reddish-brown leaves with ragged margins due to potassium deficiency.

Plate 5.—Cotton boll showing potassium-deficiency symptoms. Left, normal, large, well opened boll. Right, small, immature, partly opened boll resulting from a deficiency of potassium.

Courtesy of Pee Dee Experiment Station, Florence, S. C.

Plate 6.—Growth characteristics due to potassium deficiency. The plot at the top did not receive potash in the fertilizer. Note the premature shedding of the leaves and the immature, partly opened bolls. The normal growth of plants that received a complete fertilizer is shown at the bottom.

Plate 7.—Cotton leaves showing purplish-red color with green veins resulting from magnesium deficiency. Leaf at left is normal.

Courtesy of J. E. McMurtrey, Jr., U. S. Department of Agriculture

Plate 8.—These cotton plants did not receive magnesium. Note the purplish-red color of the lower leaves and premature shedding of foliage.

Courtesy of F. L. Davis, Louisiana Agricultural Experiment Station.

Plate 9.—Sulfur deficiency in cotton. The plant on the right did not receive sulfur in the fertilizer. Note the dwarfed growth and yellow leaves with green veins. These characteristics are similar to nitrogen-deficiency symptoms, though the green color of the veins may be more distinct in the case of sulfur deficiency. The large, normal green plant on the left received sulfur.

CHAPTER VI

Plant-Nutrient Deficiencies in Vegetable or Truck Crops

By J. J. Skinner and E. R. Purvis [1]

MANY of the symptoms of plant-nutrient deficiencies now recognized were first identified in vegetable crops. There are a number of reasons why these crops were among the first to suffer from a depletion of the soil's supply of available nutrients. Few other plants are grown on as intensive a scale, often two or more successive crops being produced on the same soil within a single growing season. Quality in vegetables will usually depend upon the speed with which the plants can be brought to the marketable stage. This requires an ample and constant supply of available nutrients in the soil to maintain rapid growth. Yet the bulk of the vegetable crops produced in the United States are grown on light-textured sandy soils of low native nutrient content. Such soils warm up early in the spring, favor the development of root crops, are responsive to applied fertilizers, and are easy to cultivate. These factors outweigh their lack of fertility. The vegetable grower has long been acquainted with the symptoms of plant deficiencies of nitrogen, phosphorus and potassium, and for years he has supplied these nutrients to his soil in the form of commercial fertilizers.

However, because of the tremendous increase in the use of commercial fertilizers throughout the world during the past two decades, the supply of many of the natural products once used in making NPK mixes has become too limited to meet the demand, or else these materials have found a more profitable market elsewhere. Blood, tankage, fish scrap, kainit, manure salts, guano and bone meal all contain important traces of essential nutrients other than nitrogen, phosphorus and potassium. As long as these were the common constituents of fertilizers, the grower was unwittingly supplying his soil with traces of nutrients just as important to crop production as those upon which the price of the fertilizer was based. This was especially true in vegetable production where larger amounts of fertilizer are normally used than are applied to most other crops. When these natural products were replaced by synthetic or highly refined materials, vegetable crops, along with other

[1] J. J. Skinner is former senior biochemist, Bureau of Plant Industry, Soils and Agricultural Engineering, U. S. Department of Agriculture, (retired); and E. R. Purvis is associate research specialist in soils, New Jersey Agricultural Experiment Station.

plants, began to show symptoms of new deficiencies. Within the past 20 years we have come to realize that many of our soils must be supplied with boron, copper, iron, magnesium or zinc, in addition to nitrogen, phosphorus and potassium, if they are to continue to produce profitable crops. We now recognize signs of hunger for these nutrients in many plants.

Other factors which have contributed to the advent of these new nutrient deficiencies are: The dwindling supplies of stable manures on farms, the improvement of vegetable varieties with a resulting increased nutrient demand to produce the higher yields made possible with these better varieties, and the injudicious use of lime. The latter factor is especially important since the pH of the soil controls to a marked degree the availability of such nutrients as boron, iron, manganese and zinc. Enthusiastic liming programs during the past few years have resulted in the overliming of many normally acid soils. When this occurs, the nutrients mentioned above may become unavailable to plants.

Just as the nutrient requirements of vegetable crops vary, the symptoms of malnutrition due to a deficiency of an essential plant nutrient will not be similar in all plants. However, the more we learn of the role of an element in plant nutrition, the better we are able to correlate the variations in the symptoms produced by a deficiency of that element in different plants. The deficiency symptoms of many nutrients are remarkably similar in a considerable number of vegetable crops. Some of the outstanding symptoms of nutrient deficiencies that have become economically important in vegetable crops will be discussed and illustrated in the remaining sections of this chapter.

NITROGEN DEFICIENCY

It is likely that symptoms of nitrogen deficiency were among the first signs of malnutrition in plants to be identified by man. There is little doubt that these symptoms are more generally recognized today than are those of most other nutrient deficiencies. The vegetable grower knows from experience that light-green to yellow leaves, coupled with retarded growth, are indications of nitrogen starvation in his crop. Experience has also taught him that a liberal and constant supply of nitrogen in the soil is necessary for the production of high-quality vegetables.

The nitrogen content of mineral soils will vary from approximately 1,000 to around 4,000 pounds to the acre, the greater part

of the element being contained in the organic fraction of the soil where it is not immediately available to plants. Since the soils normally used in the production of vegetable crops are usually low in organic-matter content and of a light sandy texture, they contain little nitrogen to begin with and rapidly lose the nutrient through leaching when it is oxidized to the nitrate form. Where vegetable crops are grown in rotation with legumes, the residues from the latter plants will supply part of the nitrogen required by the former. However, the native nitrogen supply of the soil usually furnishes but a small part of the nitrogen utilized by vegetable crops. The remainder must be supplied in the form of nitrogenous fertilizers.

All plants utilize nitrogen in both the ammonia and the nitrate form and their nitrogen requirements are generally higher in the early stages of growth. However, plants may show nitrogen-deficiency signs during any period from the seedling stage to maturity.

The symptoms of nitrogen deficiency are strikingly similar in most vegetable crops. The first indication of the deficiency is usually seen in the leaves of affected plants. These lose their normal green color and become light green to yellow. Similar color changes soon occur in the stems. The condition usually starts at the growing points of the younger leaves but rapidly spreads to all foliage. In the final stages, the entire plant may become light yellow to golden yellow in color before changing to brown.

The first sign of nitrogen deficiency in tomatoes is retardation of growth, followed by loss of the normal green color. The change in color is first noticeable in the tips of the younger leaves at the top of the plant. These leaves remain small and thin. The entire plant gradually becomes light green to pale yellow in color. From a yellowish green the color of the veins of the leaves changes to a deep purple, which is accentuated on the underside of the leaf. The stems become hard and fibrous and may take on the same deep purple color found in the leaf veins (plate 1, page 203).

Roots of nitrogen-deficient tomato plants may be more fully developed than the tops in the early stages of growth, but they finally become stunted, turn brown and die. Flower buds turn yellow and shed, a symptom apparently associated with the reduced leaf area, which in turn reduces the rate of carbohydrate production to the point where the plant is not able to support fruiting. The few fruit that do develop are small, woody and pale green when unripe, but highly colored when ripe. The yield of fruit is greatly reduced.

In cucumbers also, the early symptoms of nitrogen deficiency are exhibited by a stunted growth and a change in color of the foliage. The normal green of the leaves fades through several shades of green and yellow until, in extreme cases, all of the chlorophyll is broken down and the remaining color is pure yellow. The stems are slender and become hard and fibrous. As with tomatoes, the roots tend to develop more fully than the tops but eventually cease growth, turn brown and die.

Cucumber fruit on nitrogen-deficient plants is frequently light in color. Due to the effects of the deficiency, the cucumbers become pointed at the blossom end and the pale color is intensified (plate 2, page 204). Such cucumbers are marketed as low-grade products. A lack of nitrogen in the soil is one of the principal causes of low yields of cucumbers.

Nitrogen deficiency in radishes is likewise indicated by retarded growth, which affects both tops and roots. The leaves are small, narrow and thin, and they become yellow. The stems are slender and weak. The roots are small and imperfectly developed and have a faded reddish color when compared with radishes grown with an abundant supply of nitrogen (plate 3, page 205).

In onions, the symptoms of nitrogen deficiency usually appear early. The plants are slow in growing off, and the leaves are short and small in diameter and light green in color; later the tips turn a reddish-buff color which eventually involves the entire leaf. The plant has a distinctly stunted appearance (10, 19).

POTASSIUM DEFICIENCY

Potassium starvation has been observed in almost all truck crops and occurs generally in truck-crop soils unless they are properly fertilized. Potassium is perhaps removed from soils by vegetable crops in larger amounts than are other nutrients, and it is readily leached from the kind of soils found in the large trucking areas. Most vegetable crops quickly reflect any shortage of this element. Without sufficient available potassium in the soil, vegetable plants suffer reduced vigor, greater susceptibility to disease, impairment of growth processes, and failure to develop normally and to translocate starch, i.e., move it from one part of the plant to another in response to internal needs. On the other hand, the presence of an adequate supply of available potassium in the soil promotes the health of the plant, increases resistance to certain diseases, and offsets the effect of an oversupply of nitrogen.

Potassium-deficiency symptoms in vegetable plants are indicative of a very limited supply of available potassium in the soil. Early symptoms indicate danger, which may be avoided by applying potassium to the soil. If the deficiency is not corrected, the result may be defective plants, retarded growth, reduced yields, and economic loss.

A deficiency of potassium is recognized by a change in the color of the vegetative parts as a whole and the occurrence of spots caused by a breaking down of the tissues. Symptoms may vary with the age of plants. In soils extremely low in potash the symptoms may appear in the seedling stage, but in those with a supply that is moderate but not sufficient to support normal growth to maturity they may not appear until the fruiting stage. In soils with a medium content of potash and an abundant supply of nitrogen, potassium-deficiency symptoms may develop after a period of rapid growth. Where there is a moderate supply in the soil, potassium starvation in tomato plants may appear first at the middle of the plant and work upward, but in very deficient soils the symptoms usually appear first in the older leaves at the base of the plants.

Potassium-starved tomato plants grow slowly. The plants are stunted and the yield is small. The young leaves become finely crinkled. Older leaves turn an ashen grayish green at first, developing a yellowish green along the margins. The injury progresses from the margin toward the center of the leaflet, causing a bronzing of the tissue, which is followed by the development of large, light-colored spots between the larger veins. The affected areas often turn a bright orange color and frequently become brittle. The leaves turn brown and finally die. The stems become hard and woody and fail to increase greatly in diameter, remaining slender (plate 4-A, page 206). The roots are not well developed; they remain slender and are often brown in color, and secondary thickening does not occur.

Potassium deficiency may have a decided effect on the shape, solidity and quality of tomato fruit. The fruit on plants showing extreme deficiency may ripen unevenly and lack solidity (plate 4-B, page 206).

Cabbage plants showing potassium deficiency in its earliest stage become bronzed on the border of the leaf, and the bronzing spreads inward. As the deficiency becomes acute, the symptoms progress and are manifested by a parching of the leaf rim and the development of brown spots in the interior of the leaf (plate 5, page 207).

Potassium deficiency in brussels sprouts causes symptoms very

similar to those in cabbages. In carrots, the symptoms are manifested first in curled leaves. The rim of the leaf becomes brown, and the green of the inner portion fades to a grayish green and finally becomes bronzed.

In cucumber plants, potassium-deficiency symptoms are the characteristic bronzing and dying of the leaf margin. The bronzing gradually spreads into the leaf area between the veins. Fruit with an enlarged tip end is characteristic (plate 2, page 204).

Radishes grown in potash-deficient soil exhibit a dark-green color in the center of the leaf, a very early symptom of potassium deficiency, while the edges curl and become pale yellow to brown. Extreme deficiency is exhibited in the deep yellow to bronze color of the lower leaves and the stems. The leaves are thick and leathery. The roots are more bulbous than they would be normally (plate 3, page 205). In beets, the deficiency is manifested in a tapered root, which is nonbulbous and poorly developed.

Potash-deficiency symptoms in onions can develop early in plants that are not stunted. At the outset the tips of the older leaves assume a distinctly grayish-yellow or light straw color which gradually progresses downward as the entire leaf wilts. The wilted areas exhibit a satiny texture and a crepe-paper-like appearance (10, 19).

PHOSPHORUS DEFICIENCY

Phosphorus deficiency is most likely to become evident after land has been farmed for a number of years. For this reason the soils of the eastern trucking areas of the United States have shown the need of phosphorus first. The custom of using large quantities of phosphate fertilizer is so general in the large areas of extensive truck-crop farming, however, that phosphorus deficiency is seldom of economic importance. If commercial phosphate were not abundantly supplied to sandy truck-crop soils of low phosphate content and to the heavy soils of high clay content, which have a high fixation power for phosphorus that makes it unavailable, phosphorus deficiency in vegetables would in all probability become serious and result in great loss.

The symptoms of phosphorus deficiency in vegetable crops are slow growth and delayed maturity. Characteristic foliage symptoms are generally less pronounced than those resulting from deficiencies of some of the other plant nutrients. Some crops, suffering from phosphorus deficiency, show a tendency for the leaves to assume a darker green color than do those of normal plants. This

phenomenon is probably due to an increase in the chlorophyll concentration in vegetative tissues which are no longer growing. In other crops, purple pigmentation may appear in the leaves, or along the leaf veins. The fibrous root systems of phosphorus-deficient plants are poorly developed. The fruit of such plants ripen slowly and are relatively small in size. The seed will also be small and of light weight. Often over half of the total phosphorus content of mature plants will be found in the seed and the fruit. Vegetable crops, in common with other plants, have two periods in their growth cycle when their requirements for phosphorus are high—the early stages of plant growth, and again as the fruit and seed are maturing. The symptoms of phosphorus deficiency appear more frequently during the early stages of growth, for if the plant obtains sufficient phosphorus for vegetative growth, it can translocate a high percentage of the nutrient contained in the vegetative tissues for the production of fruit and seed. When symptoms of the deficiency do appear at the fruiting stage, it is usually too late to do anything about it.

An early symptom in tomatoes is the development of a reddish-purple color on the underside of the leaf. The color in the web of the leaf may first appear in spots and later spread over the entire leaf, with the veins finally becoming reddish purple. The foliage eventually assumes a purplish tinge. The stems are slender and fibrous. The leaves are small, and the plant is late in setting fruit (plate 6, page 208) (6). The leaves of phosphorus-deficient radishes also exhibit a reddish-purple color on the underside (plate 3, page 205). In celery, the deficiency is exhibited by poor root development and slender stalks. Phosphorus-deficiency symptoms usually appear later in the growth of the onion. Stunting occurs and soon the tips of the oldest leaves wilt and die. In some cases the affected leaves become mottled in appearance with green areas appearing among yellow and brown tissue (10, 19). The dead leaves may turn black. With most leafy crops, such as broccoli, cabbage and cauliflower, phosphorus deficiency is indicated when the underside of the leaves takes on a reddish-purple cast. This pigmentation will usually be more pronounced along the veins.

CALCIUM DEFICIENCY

Soils of the important trucking areas are generally supplied with calcium in the form of lime or in fertilizers. The latter are used generally in quantities sufficient to supply the calcium necessary for the growth of vegetable crops. A deficiency may become prev-

alent in these soils if fertilizers that do not contain calcium are used for a period of years.

Much research work has been reported on the growth of plants in calcium-free nutrient solutions. From such experiments the symptoms of calcium deficiency in some vegetable plants are well known, though its occurrence under field conditions is unusual.

A lack of calcium results in retarded vegetative growth and thick woody stems. The root tips are affected. Tomato plants suffering from the deficiency have yellow leaves on the upper part of the plant, while the lower leaves remain green. This is a distinctive characteristic; in deficiency of nitrogen, phosphorus or potassium, the lower portion of the plant exhibits discolored foliage while the upper leaves and stems remain normal. The indications are that calcium is not transferred from the older leaves at the base of the plant to the newer leaves at the top. Calcium-deficient tomato plants are weak, flabby and lacking in firmness or turgidity. The terminal buds die and the stem near the terminal becomes spotted with dead areas. Roots are short, much branched, stubby, bulbous and dark brown in color (5, 13).

Courtesy of R. P. Hibbard and B. H. Grigsby, Michigan Agricultural Experiment Station

Figure 1.—Garden-pea plants, growing in water cultures, showing calcium deficiency. Plants on the left are growing in a complete nutrient solution, those on the right in a solution lacking calcium. Lack of calcium early retards the elongation of stem; 2 weeks' growth produced the difference in height. The leaves are drying and curling under, the tendrils shriveling, and the young tissue changing to pale green or yellow (7).

Calcium deficiency in garden peas is shown by the appearance of red patches on the leaves, first near the midrib and at the ends of the small veins. As the injury increases it spreads out toward the leaf margin until the whole leaf is involved. The color changes gradually, the healthy green turning to pale green and then to white. The basal portion of the leaf loses color first, the margin remaining green longest. Calcium deficiency causes a very slow growth and a dwarfing of the plant (figures 1 and 2) (7).

SULFUR DEFICIENCY

Sulfur starvation in vegetable plants in the field is unusual. A deficiency of this plant food is seldom found in soils used for vegetable crops, particularly soils of the large trucking areas. This is perhaps because sulfur is supplied in commercial fertilizers, which are used in large quantities on most truck-crop soils, and also because the sulfur in the atmosphere is brought down by rain. Sulfur deficiency may occur in local areas where the soil conditions are unusual. Serious injury to vegetable crops in the large trucking areas from sulfur deficiency is improbable unless present fertilizer practices are radically altered.

Courtesy of R. P. Hibbard and B. H. Grigsby, Michigan Agricultural Experiment Station

Figure 2.—A detailed comparison of the difference between the shoots of young pea plants grown in a complete nutrient solution, on the left, and in one lacking calcium, on the right. The color of the leaves on the left is a deep green and the tendrils are long and active. The margins of the leaves on the right are green but the centers are white; the tendrils are short, tough and shriveled (7).

Sulfur-deficiency symptoms develop slowly in tomato plants. The appearance of the plants is similar to that of plants suffering from an incomplete supply of nitrogen. The lower leaves become yellowish green, the stems are hard and woody, and the roots are well developed and extensive. Both roots and stems are small in diameter. Sulfur-deficient tomato plants have a remarkable capacity for elongation of the stem, which is not the case with plants grown with an incomplete supply of nitrogen, phosphorus or potassium. Stems of sulfur-deficient plants, though woody and hard, increase in length but not in diameter. The plants are high in carbohydrates and sometimes in nitrogen (14).

MAGNESIUM DEFICIENCY

Magnesium deficiency in truck-crop soils is widespread in many sections of the country. Soils of the Atlantic and Gulf Coastal

Plains, where extensive areas are devoted to vegetable growing, are very low in magnesium content. The causes of the deficiency are a natural lack of magnesium rock material in the soil, extensive leaching due to heavy rainfall, and the removal of large quantities of magnesium in crops. Losses due to magnesium deficiency are of economic importance not only in the Atlantic and Gulf trucking belts, but also in many other sections throughout the country. Periodic applications of soluble magnesium fertilizer or magnesium limestone to magnesium-deficient soils are necessary to produce truck or vegetable crops of good quality. The growing of cover crops for green manure tends to conserve the magnesium supply in the sandy soils of the Atlantic seaboard trucking belt, which are subject to excessive leaching. It is essential to maintain an adequate supply of magnesium in truck-crop soils at all times.

Magnesium influences the earliness and the uniformity with which vegetable crops mature, the size of the roots, the size of the fruit, and the quality of the marketable portion of the crops. Vegetable plants develop a characteristic chlorosis, or lack of normal green color, when the magnesium supply is insufficient. The lower leaves are affected first, and in some vegetables these are practically the only leaves that become chlorotic.

Tomato plants grown in soil or in sand-nutrient solutions deficient in magnesium develop leaves that are very brittle and have a tendency to curve upward. The veins remain dark green while the areas between them become yellow, the yellow color increasing in intensity with distance from the vein. The yellow areas become deeper in color and finally turn brown and break down. The symptoms are most common in the older leaves of mature plants. From time of fruiting the deficiency may become increasingly severe. There is little effect on the stems or the fruit (plate 7, page 209).

Early stages of magnesium deficiency in cabbages are manifested by a chlorotic, mottled, puckered appearance of the lower leaves (figure 3). The advanced stage is a more severe mottling which develops into white or very pale yellow areas around the rim and at the center of the leaf. These areas decay and die. The white and yellow area at the rim of the leaf turns brown when extreme deficiency has developed (plate 5, page 207). If magnesium deficiency only is present, areas of dead tissue mark the entire leaf. If nitrogen is also a limiting factor, the entire leaf will first turn a light-green color and then become yellow before the breakdown occurs in the central portions of the areas between the veins (1).

Potassium deficiency is sometimes confused with a lack of magnesium. The former, however, appears as a bronzing of the leaf, the color developing into brown before the breakdown of tissue occurs. On the other hand, magnesium deficiency will often appear in vegetable crops after a liberal application of potassium fertilizer salts to the soil. This suggests a possible connection between the roles of the two nutrients in plant metabolism, or it may be just a matter of the substitution of limiting factors, the increased rate of

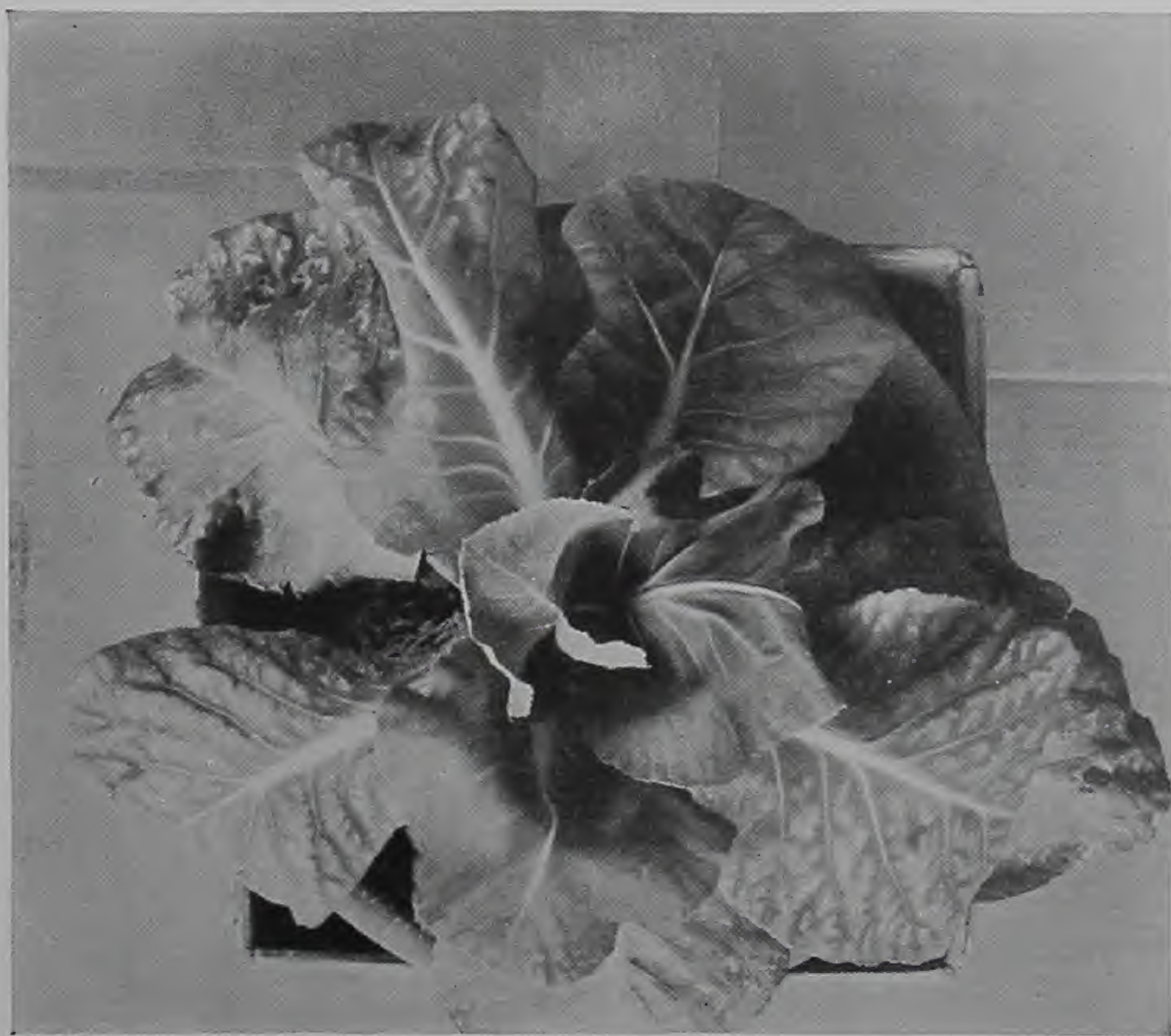


Figure 3.—Overwintered cabbage plant from field experiments showing symptoms of magnesium deficiency. Note the white, puckered, spotted area of the lower leaves, indicative of early stages of the deficiency (*2*).

Courtesy of R. L. Carolus, Virginia Truck Experiment Station, and B. E. Brown, U. S. Department of Agriculture

growth produced as a result of the applied potassium rapidly depleting the limited supply of magnesium in the soil.

Turnip leaves from plants grown under conditions of magnesium deficiency develop brown areas around the rim which dry up and fall out, while the inner areas are chlorotic and mottled (plate 8, page 210) (2).

Most vegetables are susceptible to a shortage of magnesium in the soil and show the general characteristics described here.

Magnesium deficiency in carrots is characterized by a lightening of the foliage color and the appearance of light-yellow or brown spots on the tips of the lobes of the leaflets. Deficient plants are generally smaller than those with an adequate supply of magnesium. Magnesium deficiency has seldom been identified in beets. Cucum-

bers and squash are very sensitive to any condition that may unbalance the supply of nutrients in the soil solution. These two vegetables show similar responses to magnesium deficiency. Snap beans and lima beans deficient in magnesium show the characteristic mottling and browning of the foliage described for other vegetables. The first evidence of magnesium deficiency in onions is the development of irregular elliptical-shaped areas near the ends of the leaves, almost white in color, which later disappear in a general breakdown of the affected leaves (plate 16, page 214) (10, 19).

Since sweet potatoes are generally grown on nutrient-poor, sandy soils, and since these soils must be maintained at a low pH to control the disease known as pox, it may be expected that they would be especially susceptible to magnesium deficiency. As with other plants, the deficiency first affects the older leaves. These develop yellow areas between the leaf veins while the veins remain green (plate 9, page 210). As the deficiency becomes extreme, the older leaves turn brown and dry up while the symptoms appear in newer leaves closer to the tip of the veins. In the Puerto Rican type of sweet potato, the chlorotic areas between the veins of the leaves are reddish purple in color instead of yellow. Magnesium deficiency will often reduce the yield of sweet potatoes by half, or more.

BORON DEFICIENCY

Small quantities of boron are necessary for the normal growth of most, if not all, vegetable plants. The addition of 5 to 20 pounds of borax per acre to boron-deficient soils is usually adequate for normal growth of vegetables. The range between quantities necessary for normal growth and amounts that are toxic is very narrow.

In recent years boron has been found to be an essential plant food of vegetable crops. Previously it was considered that soils ordinarily contained sufficient boron to support plant growth, but authentic cases of boron deficiency in vegetables as well as in other crops have been reported from various sections of the United States and Canada—in fact, from most parts of the world. Plants become adversely affected or die if deprived of boron. Crop failure from this cause has occurred in many widely separated sections, often causing considerable economic loss.

Boron deficiency has been noted on soils of different origin, differing in physical and chemical characteristics. It is common on soils to which lime has been applied and on sandy, leachy soils,

as well as on heavy and silty soils. The crack stem of celery on sandy soils in Florida, attributed to boron deficiency, is among the earliest cases known of the failure of a field crop from this cause. During the past few years it has been reported in Eastern, Middle Western, and Western States. Malnutrition of beets, turnips, rutabagas, cauliflower, lettuce and spinach, due to a lack of boron, has been observed in many States including Virginia, New Jersey, New York and Michigan, where it occurs in sufficiently large areas to be of economic importance. Boron deficiency is also economically important in Canada and in European countries.

The severity of boron-deficiency diseases in the field may depend on other factors beside the boron content of the soil. Soil moisture is an influential factor—in dry seasons there is greater injury from this cause. Excessive amounts of lime in the soil increase injury. The injury to vegetable crops caused by overliming has been attributed in some cases to boron deficiency, but the mechanism involved in rendering boron unavailable has not been explained.

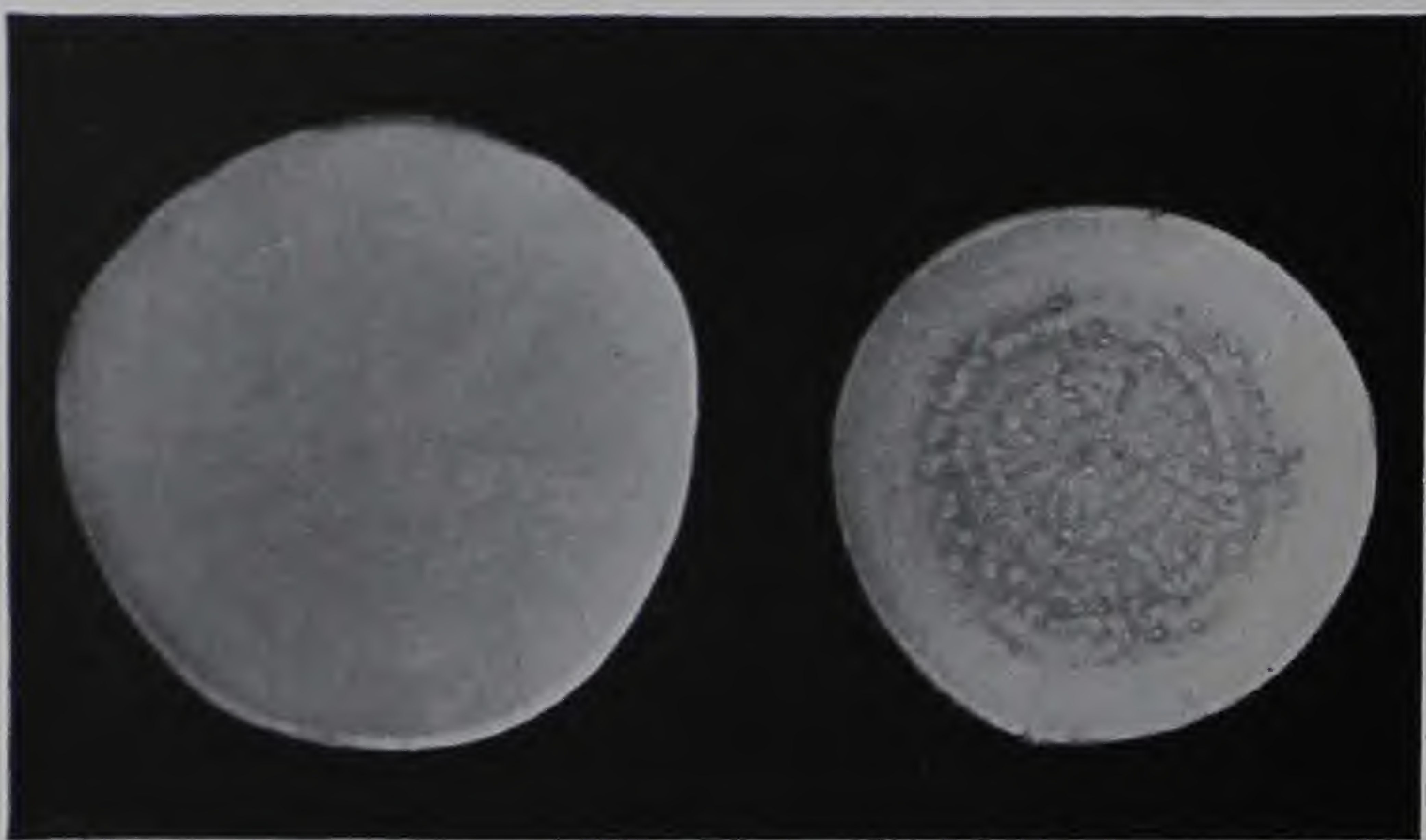
Characteristic symptoms of boron deficiency in specific vegetable plants vary widely. The crack stem of celery and the brown heart of table beets and turnips are very different, but both are due to a lack of boron.

In celery, boron deficiency first manifests itself by a brownish mottling of the leaf, usually appearing first along the margins of the bud leaves. The mottling is accompanied by brittleness of the stem and by the appearance of brown stripes in the epidermis along the ribs. Finally crosswise cracks appear on the surface of the stalk and the tissue curls outward from these breaks. The disrupted tissue soon becomes dark brown in color. Roots of the affected plant turn brown, the laterals dying back, and form small knoblike appendages at their extremities. In the final stages the plant dies. Under field conditions the deformed plant may remain alive and new growth may appear later (plate 10, page 211) (17).

Boron deficiency in table beets (16), turnips (4) and other root crops, commonly known as brown-heart disease, is manifested first by dark spots on the roots, usually on the thickest parts. The plant gradually becomes stunted or dwarfed. The leaves are smaller than normal and less numerous, and they gradually assume a variegated color, which appears as a mixture of yellow and purplish-red blotches over part or all of the leaf, while the stalks of such leaves usually show a longitudinal splitting. Frequently the affected plant has twisted leaves and exhibits a slight shortening

and discoloring of the leaf stalks in the center of the crown. The growing point may die and decay. The root does not grow to full size and under conditions of severe boron deficiency remains very small and distorted, with a rough, unhealthy, grayish appearance instead of a clean, smooth surface. Often the surface will be wrinkled and cracked (plate 11, page 211).

On a root cut through, boron deficiency may be seen as the familiar brown heart—dark-brown, water-soaked areas in the flesh at the center (figure 4). According to the severity of the deficiency, brown heart may vary from a few small, scattered, isolated spots to a large water-soaked area, or even a hollow center with all the inner flesh badly discolored.



Courtesy of R. W. Donaldson, Massachusetts Agricultural Experiment Station

Figure 4.—Interior of turnip roots showing dark center, or hollow heart, caused by a deficiency of boron. Left, normal turnip; right, boron-deficient turnip.

In tomatoes, boron deficiency has not been of economic importance and has not occurred generally. The deficiency has been observed when plants were grown in nutrient solutions free of boron. An early symptom is a blackened appearance at the growing point of the stem. The plant looks bushy owing to the growth of new leaves below the growing point of the stem. The cotyledons, or seedling leaves, and the true leaves turn a distinctly purple color while the plant is young. The stems become stunted and the terminal shoot curls inward, yellows and dies. The conductive tissue breaks down. A striking characteristic is the extreme brittleness of the petioles, or leaf stems, and the midribs. The roots show extremely poor growth and become yellow or brown in color. The fruit is frequently covered with darkened or dried areas, apparently owing to the breakdown of the tissue.

Boron deficiency in lettuce is characterized by malformation of

the more rapidly growing leaves, spotting and burning of the leaf tips, and death of the growing point of the plant (figures 5 and 6) (12). The first symptoms are retardation of growth and malformation of the younger leaves. Marginal growth ceases, and this results in a folding back of the leaf tip. The spots on the leaves increase in size and number, involving the entire leaf tip and giving it a scorched appearance. The older leaves are not noticeably affected, but all young leaves, from those first affected to the growing point itself, are involved.

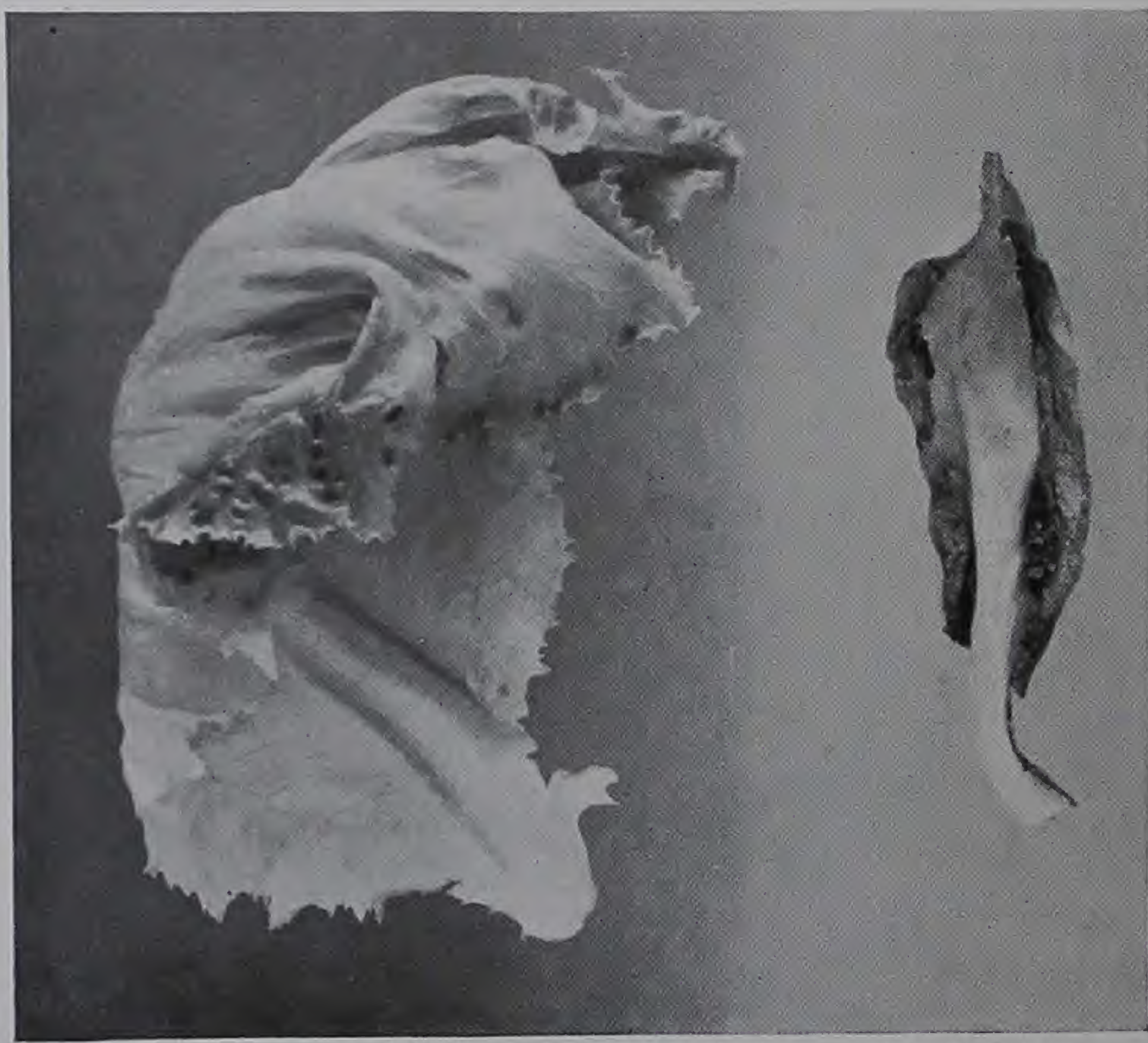
Courtesy of J. S. McHargue and R. K. Calfee, Kentucky Agricultural Experiment Station

Figure 5.—Growing point of lettuce plant showing symptoms of boron deficiency. Note the curling or folding back of the young leaves and the scorched appearance of the disfigured leaf tips (*12*).

Boron deficiency in cauliflower first appears as small, concentric, water-soaked areas in the stem and in the center of the small branches of the curd (plate 12, page 212). The external appearance may resemble the browning in brown heart of turnips. When browning is severe, both the outer and the inner portions of the head are affected. The discoloration of the curd may appear at various stages of maturity, and it increases with growth. In a cauliflower plant affected with boron deficiency, the smaller leaves around the curd may be deformed and stunted (3).

Boron deficiency gives onion plants a characteristically stunted, distorted appearance. Leaf color varies from dark gray green to deep blue green, the youngest leaves developing conspicuous yellow and green mottlings. Shrunken areas appear, followed by ladderlike transverse cracks on the upper sides of the basal leaves. The leaves become stiff and brittle (plate 17, page 214) (10, 19).

Boron deficiency first manifests itself in sweet potatoes by a restriction of the terminal growth of the vines and a shortening of



Courtesy of D. I. Arvon and S. B. Johnson, California Agricultural Experiment Station

Figure 6.—Normal leaf (left) and boron-deficient leaf (right) resulting from growing lettuce in sand and nutrient-solution cultures.

the internodes. As the disturbance develops, petioles become curved and the terminals become stunted and distorted. The older leaves turn yellow and are prematurely shed (figure 7). Tubers from deficient vines show varying degrees of both external and internal degeneration. They are misshapen and the skin is rough and leathery in texture. Dumbbell-shaped, lopsided and spindle-shaped malformations are common. Severely affected tubers show surface cankers, sometimes covered with a hardened, dark exudate (figure 8). Affected tubers may show evidence of internal breakdown, similar to that produced by boron deficiency in turnips and beets. Varying in size, these internal necrotic areas occur indiscriminately throughout the fleshy part of the tuber but seem to be most prevalent in the cambial zone near the periphery (15).

Courtesy of C. J. Nusbaum, South Carolina Agricultural Experiment Station

Figure 7.—Normal sweet potato vine on left. Note the long straight petioles, well-spaced internodes and actively growing terminal. Boron-deficient plant on right shows a stunted, gnarled type of growth, short internodes, and curled petioles. Note the distorted terminal bud and the premature shedding of leaves.

Figure 8.—Sweet potato roots showing typical boron-deficiency symptoms. Note the malformation of the roots and the surface cankers covered with blackened exudate.

Courtesy of C. J. Nusbaum, South Carolina Agricultural Experiment Station

IRON DEFICIENCY

Iron is indispensable for plants and is abundantly supplied in nearly all soils except those that are calcareous and alkaline. The solubility of iron is governed by the the soil reaction; in acid soils it is comparatively soluble. The addition of organic matter, such as crop residues and stable manure, increases the supply of iron available to crops.

Courtesy of D. R. Hoagland and D. I. Arnon, California Agricultural Experiment Station

Figure 9.—Iron-deficiency symptoms shown by tomato plants grown in nutrient solutions. The leaf on the left is from a plant grown in a complete nutrient solution; the one on the right was grown in a solution containing no iron (*5*).

Iron deficiency in truck or vegetable crops is not of economic importance on the acid soils of the large trucking belts. In the alkaline regions of the United States, however, a chlorosis due to iron deficiency is important with some plants.

The outstanding symptom of iron deficiency is usually the de-

velopment of yellow leaves on the upper parts of the plants. The terminal growth is the first part affected. In tomato plants (figure 9), chlorosis of the young leaves, with little necrosis or dying of tissues, appears to be the dominant symptom.

Iron occurs in greatest concentration in the leaves of vegetable plants. These plants vary in their susceptibility to chlorosis associated with inactivity of iron induced by the presence of lime.

COPPER DEFICIENCY

Copper is an essential plant food for vegetable and other crops. Applying it to some kinds of soil stimulates growth and results in the production of normal plants, and without it crops fail. Copper is a normal constituent of all plants. The fact that seeds are high in copper suggests that this mineral is especially important for plants grown for seed.

Available evidence indicates that copper deficiency in vegetables is confined to those grown on dark-colored soils, such as the Portsmouth soil types, and on peat and muck. Abnormal growth of vegetable crops on peat soils of Michigan and Delaware, caused by copper deficiency, has been noted. The addition of 100 to 200 pounds of copper sulfate per acre to peat soils in western New York was found necessary to produce normal truck crops. On the sawgrass peat soils of the Everglades of Florida vegetable crops will not make normal growth without the addition of 20 to 30 pounds of copper sulfate per acre. There have been reports of copper deficiency in plants growing on peat soils in many other parts of the world. Copper deficiency is of economic importance in vegetable production in large areas of this class of soil.

Most mineral soils contain sufficient copper to support normal crops of vegetables, except possibly some that are very sandy and leachable.

The quantities of copper sulfate that have been used on soils to correct the deficiencies noted vary from 20 to 200 pounds per acre. Some peat soils have a high fixing power for copper compounds so that relatively heavy applications are necessary to produce the desired effect.

A deficiency of copper may not cause as distinct color characteristics in the foliage of vegetable crops as do deficiencies of other plant foods. There are some outstanding characteristics noted in field-grown plants in dark-colored soils, however, as well as some definite characteristics observed in plants grown in nutrient solu-

tions in the greenhouse. The leaves of affected plants do not maintain their firmness. The foliage exhibits a chlorotic condition which gives it a bleached appearance; this may be corrected by washing or spraying the leaves with a weak copper sulfate solution. Chlorotic lettuce grown on unproductive muck soil deficient in copper has become normal after being dusted with copper sulfate.

Copper-deficiency symptoms in tomatoes include very stunted growth of shoots and exceedingly poor root development, dark bluish-green color of foliage, curling of leaves and absence of flower formation, development of chlorosis, and a lack of firmness in leaves and stems (figure 10). Leaves of copper-deficient lettuce plants become bleached and chlorotic, the stem of the leaf and the rim being affected first (figure 11).

Courtesy of D. R. Hoagland and D. I. Arnon, California Agricultural Experiment Station

Figure 10.—Tomato leaves from plants grown in nutrient solutions. On left, leaflet from plant grown in copper-deficient solution; in center, in a complete nutrient solution; and on right, in a zinc-deficient solution. A deficiency of either copper or zinc has produced small leaflets as compared to those of the normal plant. The copper-deficient plant has small stems and chlorotic leaves which are curled inward. The zinc-deficient plant has normal-size stems with leaves resembling those in "little-leaf" of fruit trees (*8*).

Onions grown in peat soils in New York exhibit copper deficiency in an abnormal, thin scale of a pale yellow color (plate 14, page 213). The application of copper sulfate at the rate of 100 to 300 pounds

per acre increased the thickness of the onion scales and changed the color from pale yellow to a brilliant brown. Copper-deficient onions lack solidity and firmness (11).

In cases of copper deficiency as extreme as on the Florida soils mentioned, truck-crop plants fail entirely to grow. In less extreme cases growth is very slow and stunted.

Courtesy of D. I. Arnon and S. B. Johnson, California Agricultural Experiment Station

Figure 11.—Lettuce leaflets from plants grown in nutrient solutions. Left, leaflet from normal plant grown in a complete nutrient solution; right, leaflet grown in copper-deficient solution. Copper deficiency has caused reduced growth and malformation of the leaf, which exhibits chlorosis; the plant is weak and lacks firmness. The chlorosis appeared first on the stem and the outer rim of the leaf.

ZINC DEFICIENCY

Only a few cases of zinc deficiency in vegetable crops have been reported. It has been proved by greenhouse demonstrations that zinc is essential to the normal development of some plants, including beans, squash and mustard, but in field-grown vegetables zinc deficiency has not become of economic importance except on unusual soils. The application of zinc salts to the soil or the culture medium was effective in producing normal growth.

Squash (figure 12), mustard and tomato plants grown in zinc-deficient soils in the greenhouse at the California Agricultural

Experiment Station exhibited zinc-deficiency symptoms. Some of the plants had extremely mottled leaves with necrotic, or dead, areas. Squash was especially affected. Other plants had leaves of a uniform chlorotic appearance. Abnormally small leaves, yellow or mottled, were frequently produced, especially by tomato and mustard plants, which resembled those in "little-leaf" of zinc-deficient fruit trees. Tomato plants sometimes gave evidence of leaf injury (figure 11) when only a few inches high. Symptoms developed by plants grown in nutrient solutions containing no zinc have characteristics similar to those shown by the same kinds of plants on zinc-deficiency soil in the field.

Courtesy of D. R. Hoagland, W. H. Chandler, and P. L. Hibbard, University of California

Figure 12.—Leaf of squash plant, showing zinc-deficiency symptoms, grown in nutrient solution without the addition of zinc (*9*).

Zinc deficiency in bean plants, as observed in the field on peat soils of Florida by the Florida Everglades Experiment Station, is exhibited in symptoms similar to those discussed for squash and tomatoes in nutrient solutions and in soil in pots.

MANGANESE DEFICIENCY

Manganese is a common constituent of soils and plants. The quantities present in both vary greatly, but there is little correlation between the total manganese in soils and that in the plants growing in the soils. The availability of manganese to the crop is governed more by the acidity of the soil and the reducing action of manganese in the soil than by the quantity present.

Deficiency of manganese in soils, as demonstrated by the growth of plants, is confined principally to soils that are nonacid or calcareous. The deficiency has been noted in local sections of the trucking areas of various parts of the country and is of economic importance in some places, especially on overlimed and calcareous soils of the Atlantic seaboard. Manganese is sometimes deficient in acid soils, and when the deficiency occurs in decidedly acid soils it is thought to result from the leaching of soluble manganese, which may be pronounced in soils that are very sandy.

Application of manganese to the soil has prevented chlorosis of

tomatoes and other truck crops on the calcareous soils of Florida where crops failed to grow without it. Normal growth and good yields have resulted.

Manganese deficiency in soils can be corrected by annual applications of 50 to 100 pounds of manganese sulfate per acre. The requirement, however, may vary widely. Soils that are highly calcareous, overlimed, or acid, leachable and sandy will probably require more frequent applications for successful production.

From work of J. J. Skinner, U. S. Department of Agriculture, and R. W. Ruprecht, Florida Agricultural Experiment Station

Figure 13.—Tomatoes on calcareous soil of Florida on which vegetables do not grow unless manganese is supplied. Center, commercial fertilizers were applied at the rate of 1,200 pounds per acre. On sections of the field to the left and right, 100 pounds per acre of manganese sulfate was added to the commercial fertilizer (*18*).

In the foliage of tomato plants, manganese deficiency manifests itself first as a lightening of the green color, which gradually turns to yellow, in the leaf areas farthest from the major veins. As the condition progresses the yellow becomes more marked and extensive and the veins remain green, giving a characteristic mottled appearance to the leaf. Eventually the foliage may become completely yellow, and in many cases necrosis sets in, appearing at first as small brown pin points centering in the yellow areas farthest from the veins and expanding until larger dead areas indicate complete breakdown of the tissue. Growth is spindling, little or no blossoming takes place, and no fruit forms. Retardation of growth and chlorosis indicate failure of the leaves to function normally owing to inadequate synthesis of chlorophyll (20).

Courtesy of D. R. Hoagland and D. I. Arnon, California Agricultural Experiment Station

Figure 14.—Characteristic mottling on a tomato leaflet as a result of manganese deficiency. On left, leaflet from a plant grown in a manganese-free nutrient solution; on right, in a similar solution containing manganese.

Manganese starvation in tomatoes has been widespread, having been observed in regions extending from Florida to the northern trucking belt. In severe cases, as in the calcareous soils of Florida, plants fail and do not produce fruit (figure 13).

The characteristic, striking form of chlorosis in manganese-deficient tomatoes manifests itself in greenhouse-grown plants and in plants grown in nutrient solutions (figures 14 and 15) just as it does in plants grown in various types of soil in the field.

In spinach, the chlorosis appears first at the growing tips and gradually extends throughout the plant (plate 13, page 212). The normal green color fades from the web of the leaf, leaving it pale green to golden yellow. The green color persists longest along the principal veins. After some time white dead areas may appear between the veins of the leaves. The gradual yellowing of spinach

Courtesy of D. R. Hoagland and D. I. Arnon, California Agricultural Experiment Station

Figure 15.—Manganese deficiency as exhibited in tomato leaves from plants grown in nutrient solutions in the greenhouse. Left to right, progressive stages of manganese-deficiency symptoms in tomato leaflets.

leaves has caused some confusion of manganese deficiency with "spinach yellow," a mosaic disease.

In table beets, the symptoms are somewhat different owing to the large amount of red and purple pigments in the plants. When manganese is deficient, the leaf gradually takes on a deep red to purple color instead of becoming progressively yellow. As with spinach, the color change is most definite between the veins, where eventually dead areas appear. Beets in soils extremely deficient in manganese make little growth of either roots or tops.

From work of J. J. Skinner, U. S. Department of Agriculture, and R. W. Ruprecht, Florida Agricultural Experiment Station

Figure 16.—Cabbage leaves from plants grown on field plots in manganese-deficient calcareous soil in Florida. Left, from plot fertilized with nitrogen, phosphorus and potassium but no manganese. Right, from plot fertilized with manganese in addition to the other nutrients (*18*).

Manganese-deficient snap beans grow normally for a short period, the first symptom to appear being a loss of green color in the trifoliate leaves. The yellowing does not spread to the cotyledonary or seed leaves until late in the development of the deficiency. At first the trifoliate leaves show a faint mottling, the tissue near the veins remaining green longer than the islets of tissues between the veins. Growth is retarded when these symptoms appear, and the chlorotic leaves do not attain normal size. A few days only may elapse between the time of the appearance of the first mottling and

the time when the whole leaf turns a golden yellow. Small brown spots, near and parallel to each side of the midrib and veins between the lateral branches, may appear before the leaf becomes completely yellow (plate 15, page 213) (20).

When manganese becomes deficient in cucumbers, the web of the leaf begins to change from green to yellowish white, while the regions along the veins and midribs remain green. The stems and leaves remain small in size, weak and slender. Frequently the blossom bud turns yellow. Cabbages (figure 16) and peppers exhibit somewhat similar characteristics. In all these plants growth is stunted and yields are reduced (18).

The manganese-deficiency symptoms described and illustrated are characteristic for most vegetable crops. The foliage symptoms exhibited in plants grown in nutrient solutions, in soil in pots in the greenhouse, and in the field are very similar.

MOLYBDENUM DEFICIENCY

Molybdenum is the latest mineral nutrient to be established as essential to the normal growth of plants. Although soil deficiencies of this nutrient have been previously reported from Australia, New Zealand and Europe, the report of Walker (21) is believed to be the first instance of its detection in soils of the Western Hemisphere. Working with three serpentine soils from different locations in California, Walker found that tomatoes grown on these soils, under greenhouse conditions, developed a peculiar yellowing and curling of the leaves. The symptoms appeared in about two weeks. Often the plants were transplanted, and the symptoms were readily corrected by an application of sodium molybdate sufficient to supply one pound of molybdenum per acre. This application was made by painting the leaves with a sodium-molybdate solution containing 100 parts per million of molybdenum and by the infiltration of a 10-part-per-million molybdenum solution into a cut section of a terminal leaflet. Recovery occurred in from 4 to 5 days with all treatments.

The first symptoms of the deficiency are the yellowing and curling of the first or second pair of true leaves. Later all true leaves become mottled, the veins remaining light green and shading into the chlorotic areas between. These symptoms are portrayed in figure 17. Eventually the chlorotic areas become puffed in appearance and a marked up-curling of the leaflet margins occurs. In the final stages the tips of the leaflets and areas along the leaf margins

shrivel and die. New-formed leaves are green at first but become chlorotic and curled as they expand.

Although the economic importance of molybdenum deficiency in soils cannot as yet be estimated, it appears that lack of this element may be one of the important factors responsible for the stunted growth common to serpentine barrens.

Figure 17.—Molybdenum deficiency in tomato. Note distinctive mottling and curling of older leaves, pale green color of veins, and puffed appearance of chlorotic areas.

Courtesy of Richard B. Walker, California Agricultural Experiment Station

SUMMARY OF DEFICIENCY SYMPTOMS IN VEGETABLES

The symptoms of nutrient deficiencies that develop in plants growing in the field will often vary somewhat from those produced in plants grown under controlled greenhouse conditions. There are several sound reasons why this should be true. Deficiency symptoms encountered in the field are seldom as extreme, or as clearly defined, as are those which are artificially produced since, under field conditions, the deficiency of a nutrient is seldom as absolute as in the latter case. Disease and insects will often produce plant symptoms closely resembling those resulting from nutrient deficiencies, or these symptoms may partially or entirely mask the signs of plant hunger. In a similar way, symptoms of a deficiency of a specific nutrient will be modified by the available supply of other nutrients. Thus the symptoms of magnesium defi-

ciency in plants growing on soils having a high level of available potassium will be more extreme than those of plants growing on soils having a lower level of available potassium. The symptoms of boron deficiency are exaggerated under conditions of high nitrogen supply. Deficiency symptoms of two or more plant nutrients may develop simultaneously and result in abnormalities which are not specific for either deficiency.

Although deficiency symptoms alone are not sufficient to warrant the report of a new deficiency within a given area, once that deficiency has been established by supporting chemical analyses of plants and soil, the extent and reoccurrence of the deficiency may be verified by a survey of the prevalence of the symptoms within the fields of the area.

The characteristic symptoms of the nutrient deficiencies of vegetable crops which have been discussed in this chapter are summarized in the following key:

KEY TO PLANT-NUTRIENT DEFICIENCIES IN VEGETABLE CROPS

	Element deficient
A. Deficiencies producing distinct color changes in foliage.	
B. Symptoms first apparent in young leaves.	
C. New leaves develop light-yellow color, first between veins. Later entire leaf becomes yellow in color. Necrosis and dying of tissue usually absent. Usually restricted to alkaline or overlimed soils	Iron
C. Chlorosis appears first between leaf veins of new leaves and then spreads to older leaves. Veins remain green even in advanced stages of deficiency. Chlorotic areas become brown or transparent, and ultimately marked necrosis of affected tissue occurs. Deficiency more general on alkaline or overlimed soils although known on acid soils	Manganese
C. New leaves abnormally small and mottled with yellow, or uniformly chlorotic. Necrotic, or dead, areas common	Zinc
B. Symptoms first apparent in old leaves.	
C. First indication, ashen gray-green leaves at base of plant. Leaves develop a bronze and yellowish-brown color. Leaf margin becomes brown. Specks develop along veins of leaf. Tissue deteriorates and dies. Roots poorly developed and brown. Stems slender, become hard and woody	Potassium
C. Chlorosis first appears between veins of old leaves while veins remain green. Leaf becomes brittle and its margins curl upward. Chlorotic areas turn brown and die. Reddish-purple pigmentation instead of chlorosis with some crops. Occurs most frequently on acid soils	Magnesium
C. Distinctive mottling occurs in older leaves with veins remaining light green. New leaves green at first but become mottled upon expansion. As deficiency is prolonged, puffing of chlorotic areas occurs, leaves curl inward, and necrosis sets in along leaf tips and margins	Molybdenum

	Element deficient
A. Deficiencies affecting primarily the growing tissues of roots and stems.	
B. Symptoms seldom apparent on older growth.	
C. Stems thick and woody with vegetative growth retarded. Root tips die and snuff off with formation of small bulblike enlargements on remaining tips. New leaves chlorotic while old leaves remain green. New growth lacks turgidity. Terminal buds die in extreme cases.	Calcium
C. New bud leaves and petioles light in color, brittle, and often deformed in shape. Internodes short with rosetting pronounced at shoot terminals. In advanced stages, terminal buds die and new growth develops from buds below. Root growth greatly retarded with dark colored, corky areas forming in bulbous roots of such crops as beets, turnips and radishes. Hollow stem is a common symptom in cabbage and cauliflower, and crack stem in celery.	Boron
A. Deficiencies with localized symptoms.	
B. Retarded growth with leaf chlorosis.	
C. Leaves lack turgidity and exhibit a chlorotic condition as if bleached. Growth of entire plant greatly retarded. Most prevalent on soils high in organic matter, and on peats and mucks.	Copper
C. Retarded growth with stems slender, fibrous and hard. Normal green of leaves fades to solid pattern of yellow-green. Plant may become entirely yellow in extreme cases. Roots often show greater development than tops in earlier stages of deficiency but finally become stunted, turn brown and die.	Nitrogen
C. Lower leaves become thick and firm and develop yellowish-green color. Stems are hard, woody and abnormally elongated and spindly. Root system extensively developed.	Sulfur
B. Retarded growth without leaf chlorosis.	
C. Stems slender and woody. Leaves small and often darker green than normal. With many crops, undersides of leaves develop reddish-purple cast. Development of fibrous roots greatly restricted. Setting of fruit and maturity delayed.	Phosphorus

NOTES ON CORRECTIVE MEASURES FOR NUTRIENT DEFICIENCIES IN VEGETABLE CROPS AND SOILS

Deficiencies of nitrogen, phosphorus and potassium are readily corrected through the application of a suitable grade of commercial fertilizer. On light soils, nitrogen is readily lost through leaching, and potassium only slightly less so. Side dressings with materials containing one, or both, of these nutrients are often beneficial after heavy rains. Phosphorus is rapidly fixed in an unavailable form in acid soils.

Calcium and sulfur are rarely deficient in vegetable soils since both nutrients are supplied in common fertilizers and calcium is a principal constituent of lime.

Magnesium deficiency is readily corrected through the use of dolomitic lime. Where it is undesirable to apply lime, magnesium can be supplied to the soil in the form of soluble magnesium salts. Usually 30 to 40 pounds of magnesium oxide per acre are sufficient.

Copper deficiency occurs most frequently on peat soils of high organic-matter content. The deficiency is corrected by the application of copper sulfate with

recommended rates varying from 20 to 200 pounds to the acre. The smaller amount is usually sufficient.

Manganese deficiency may be corrected by applying manganese sulfate to the soil at the rate of 50 pounds to the acre, or by spraying the affected plants with a weak solution of manganese sulfate (0.25 percent by weight).

Boron deficiency is corrected by the application of borax, or boric acid, to the soil, or directly to the plants as a spray. Rates of application vary from 5 to 50 pounds per acre, there being great variation in the tolerance and requirements of different crops for this nutrient.

Zinc deficiency may be corrected by applying zinc sulfate to the soil at the rate of 20 to 30 pounds per acre, or by spraying affected plants with a 0.50 percent zinc sulfate spray.

Iron deficiency may be corrected by acidifying the soil, or by spraying affected plants with a weak solution of iron sulfate (0.25 percent by weight).

Molybdenum deficiency has been reported only from California. It may be corrected by application of sodium molybdate at the rate of approximately 2 pounds to the acre.

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Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station

Plate 1.—Stems and leaves of tomato plants grown under conditions of nitrogen shortage, showing, in the specimen on the right, the pale-green color of the tips of plants, the purple ribs of the underside of the leaves and stems, and the pale-green leaves fading to yellow; and, on the left, the golden-yellow leaves with hard, fibrous, bronzed stems manifesting extreme nitrogen deficiency.

1 2 3

Courtesy of I. C. Hoffman, Ohio Agricultural Experiment Station

Plate 2.—Cucumbers and leaves grown in field plots on Wooster silt loam, with (1) complete fertilizer, (2) no potash, and (3) no nitrogen. Nitrogen-deficient plants are small, leaf veins are pale green with areas between pale yellow or light brown. Blossom ends of cucumbers are pale yellow to brown and pointed. Potassium deficiency is exhibited by a bronzed, decayed area around the rim of the leaf and by fruit with enlarged tip end and undeveloped stem end.

Courtesy of S. F. Thornton and Mack Drake, Indiana Agricultural Experiment Station

Plate 3.—Radishes grown in a sand-soil mixture in pots, fertilized with (1) ammonium nitrate, dicalcium phosphate, and potassium chloride; (2) potassium omitted; (3) phosphate omitted; and (4) nitrogen omitted.

A, Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station;
B, Courtesy of I. C. Hoffman, Ohio Agricultural Experiment Station

Plate 4.—A, potassium shortage in tomato leaves. Upper left and lower right, early stages; center, later stage; upper right and lower left, well-developed symptoms. B, tomatoes from potassium-deficient plants, left, and from normal plants, right.

A, B and C, Courtesy of J. B. Hester, Virginia Truck Experiment Station;
D, Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station

Plate 5.—A, early stage, and B, late stage of potassium deficiency in cabbage leaves from plants grown in field plots on a typical southeastern truck soil. C is a normal cabbage leaf. Leaf A shows bronzing between the veins of the inner part. Leaf B shows brown spots. D, Advanced stage of magnesium-deficiency symptoms developed in sand culture. The mottled spots have turned pale yellow to white, and, with the rim of the leaf, will turn brown, decay, and die.

Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station

Plate 6.—Tomato leaflets, stalk, and leaves exhibiting phosphorus-deficiency symptoms, showing reddish-purple veins on the underside of the leaflets and on the stems of tomato plants grown in nutrient solution-sand cultures.

Courtesy of V. A. Tiedjens, New Jersey Agricultural Experiment Station

Plate 7.—Various stages of magnesium-deficiency symptoms in tomato leaves from plants grown in nutrient solution and sand cultures—early stage in leaf at the top and severe stage in leaflet at lower left; center and lower right, intermediate stages. The early deficiency symptoms are exhibited by pale-yellow areas between the veins of the leaves. In the later stages these develop into brown and black areas.

Courtesy of R. L. Carolus, Virginia Truck Experiment Station, and B. E. Brown, U. S. Department of Agriculture

Plate 8.—Leaves (left) from normal and (right) from magnesium-deficient turnip plants, both grown in field plots at the Virginia Truck Experiment Station. The outline of the magnesium-deficient leaf is ragged owing to disintegration of the outer edge. The inner areas are very chlorotic.

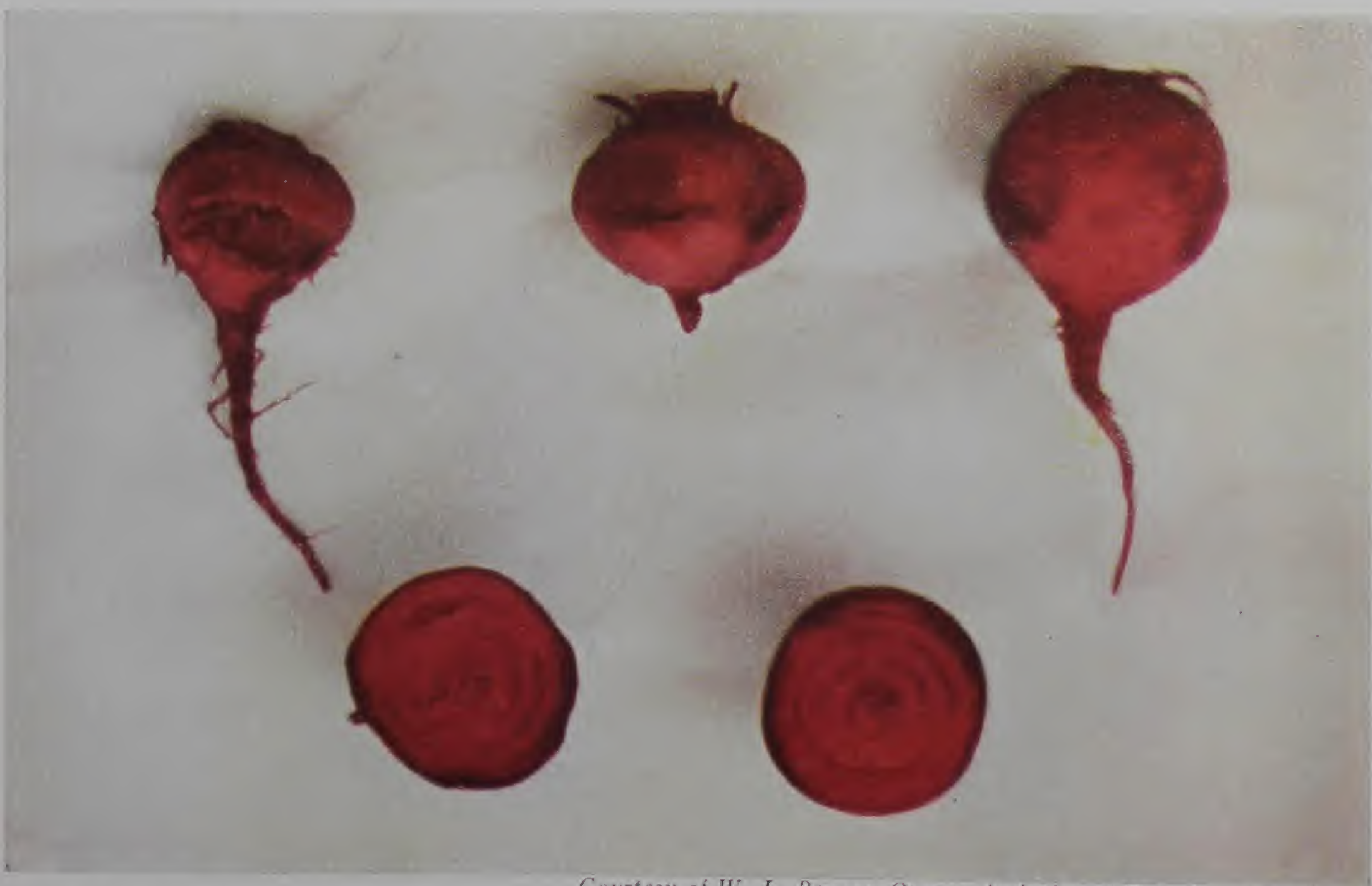
Courtesy of Soils Department, New Jersey Agricultural Experiment Station

Plate 9.—Magnesium-deficient leaves from field-grown sweet potato plant. Terminal leaves on same vine were normal in color.

1 2 3

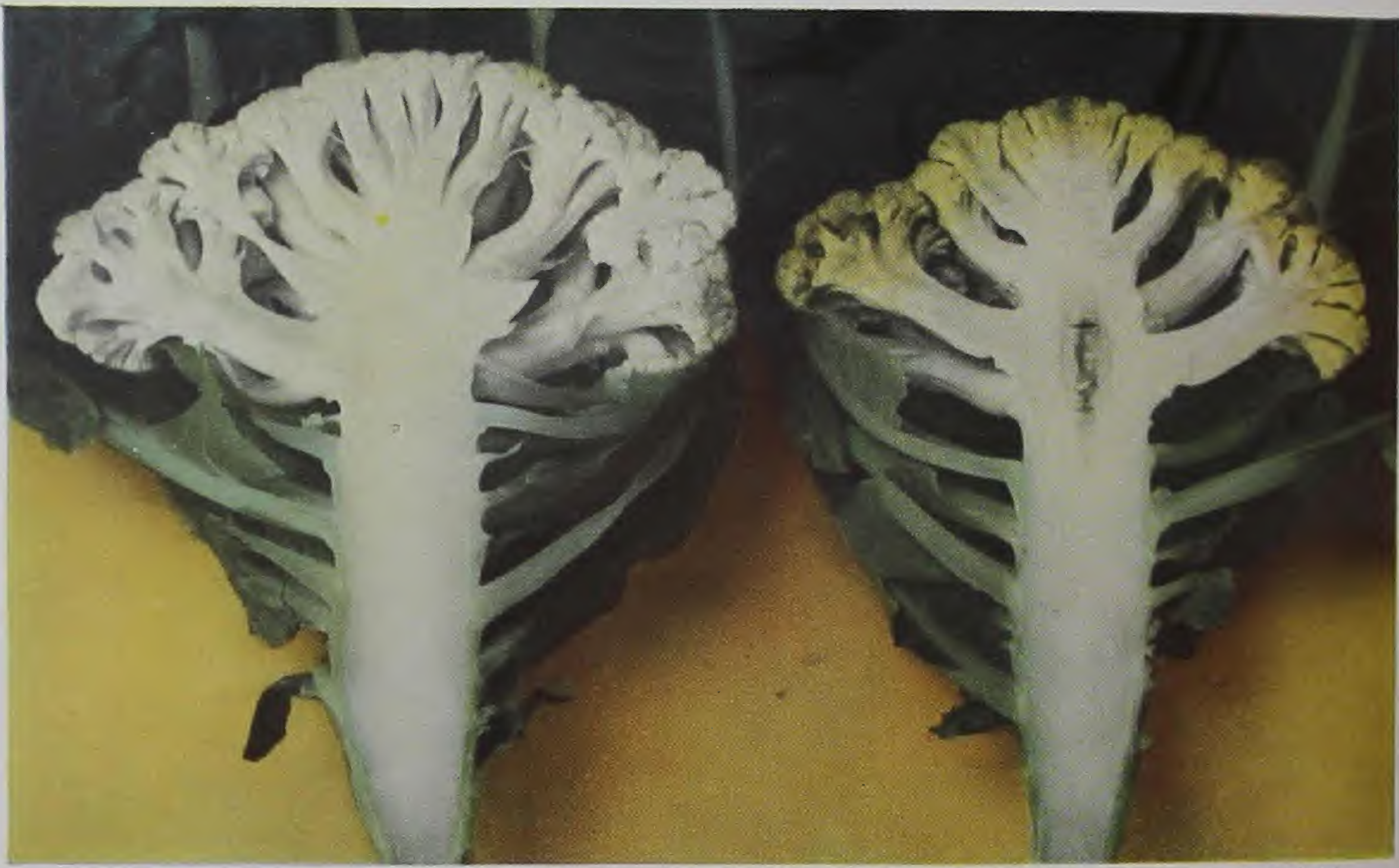
Courtesy of W. L. Powers, Oregon Agricultural Experiment Station

Plate 10.—Celery plants grown in boron-deficient soil. (1) Healthy plant grown in soil to which boron was added; (2) and (3) plants showing crack stem and decay due to boron deficiency.



Courtesy of W. L. Powers, Oregon Agricultural Experiment Station

Plate 11.—External and internal appearance of beets grown in a boron-deficient soil.



Courtesy of C. H. Dearborn, H. C. Thompson, and G. J. Raleigh, New York (Cornell) Agricultural Experiment Station

Plate 12.—Cauliflower grown in a boron-deficient soil, showing hollow stem and bronzing, symptoms of boron deficiency. Left, normal plant grown in soil receiving 10 pounds of borax per acre; right, plant grown in soil to which no borax was added.

Courtesy of Soils Department, New Jersey Agricultural Experiment Station

Plate 13.—Manganese-deficiency symptoms in field-grown spinach plant. Note mottling and crinkling of leaves and spots of dessicated tissue.

Courtesy of J. E. Knott, New York (Cornell) Agricultural Experiment Station

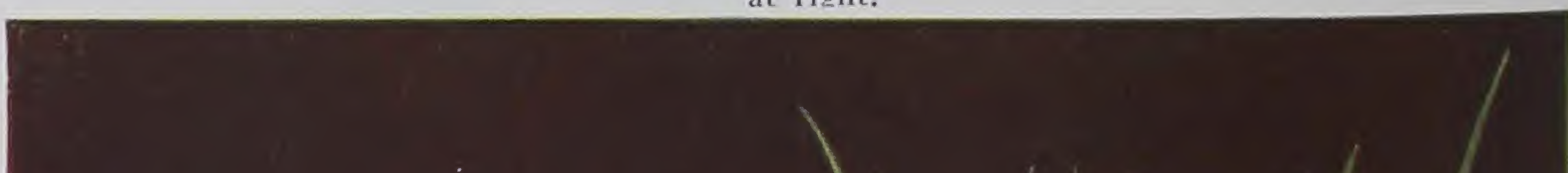
Plate 14.—Effect of copper sulfate on color of onion scales. (Onions grown on copper-deficient peat soil.) Left to right: No copper, 100 pounds, 200 pounds, and 300 pounds of copper sulfate per acre. The thickness of the scale of the onions as well as the brown color increased as more copper was added to the soil.

Courtesy of J. B. Hester, Virginia Truck Experiment Station

Plate 15.—Leaves from normal and manganese-deficient bean plants grown on a neutral truck-crop soil at the Virginia Truck Experiment Station. Left, normal leaf; center, leaf showing early stages of manganese deficiency; right, leaf showing late stages of manganese deficiency.

Courtesy of G. V. C. Houghland, Bureau of Plant Industry, Soils and Agricultural Engineering, U. S. Department of Agriculture

Plate 16.—Magnesium-deficiency symptoms in onions. The first symptoms to appear are irregular elliptical-shaped areas, almost white in color, near the ends of the leaves (11). Normal plant at right.



Courtesy of G. V. C. Houghland, Bureau of Plant Industry, Soils and Agricultural Engineering, U. S. Department of Agriculture

Plate 17.—Boron-deficiency symptoms in onions. Note marked stunting and distortion of growth. Leaf color varies from dark gray green to deep blue green, becoming mottled with yellow and green in the youngest leaves. The leaves become very stiff and brittle, and ladderlike transverse cracks appear on the upper sides of the basal leaves (11). Normal plant on right.

CHAPTER VII

Nutrient-Deficiency Symptoms in Deciduous Fruits

By O. Wesley Davidson and Wesley P. Judkins[1]

THIS chapter describes in some detail the symptoms of nutrient deficiencies observed in apples, peaches, strawberries and grapes. Other deciduous fruits are included only incidentally because of the relative infrequency with which nutrient deficiencies, other than that of nitrogen, have been encountered in these crops.

In general, the symptoms described for apples resemble very closely those for corresponding deficiencies in other pome fruits, and those described for the peach resemble the symptoms found in other stone fruits. Differences in manifestation are more a matter of degree than of kind. In fact, one who is familiar with the symptoms of a particular nutrient deficiency in the apple or peach should be able to identify a lack of the corresponding nutrient in deciduous small fruits as well as in other tree fruits.

A key to deficiency symptoms in deciduous tree fruits is given at the end of the chapter.

When different kinds of fruit are grown in the same district, it is not uncommon to find different species affected by the same deficiency. Thus, on light sandy soils, peaches, apples and pears are prone to develop nitrogen deficiency. In regions where boron troubles are common, and apples, pears and cherries are grown, all may develop a deficiency of this nutrient. Likewise, in parts of California where zinc deficiency is common, apples, peaches, cherries, apricots and walnuts are affected. Nevertheless, there may be marked differences in the susceptibility of one kind of fruit as compared with another to the same nutrient deficiency.

APPLES

Bearing apple trees are large plants and as such have a capacity to store comparatively large quantities of nutrients. Moreover, their seasonal period of rapid vegetative growth may be short, whereas the absorption of nutrients by the roots is known to continue throughout nearly the entire year in some fruit regions and during a much longer time than top growth in all locations. Be-

[1]O. Wesley Davidson is professor and research specialist in ornamental horticulture, Rutgers University; and Wesley P. Judkins is associate professor and associate pomologist, Ohio State University.

cause of these conditions apple trees require only a moderate degree of soil fertility, and they are relatively slow in responding to a nutrient deficiency. For the same reason numerous and contradictory recommendations are found concerning the fertilization of this crop.

Deficiencies of all the major and most of the minor nutrients have been known to occur in various commercial apple orchards throughout the United States. The manifestations of these deficiencies are not greatly unlike those described for tobacco. In well-developed stages the symptoms of each nutrient deficiency may be recognized readily by those familiar with them. In the early stages, however, deficiencies other than those of nitrogen and boron would be difficult to identify with assurance by means of the tree symptoms alone. For the identification of such deficiencies it may be convenient to refer to plant tissue tests, or to indications in cover crop or sod plants, or to soil analyses.

Nitrogen Deficiency

Most apple growers are familiar, in a general way, with some of the symptoms of nitrogen deficiency in their trees. This is the most common nutrient deficiency in commercial apple orchards and the one that is most readily corrected. There are, however, an infinite number of degrees of nitrogen deficiency. Only a severe deficiency of this nutrient causes injury to the tissues of a tree, but all degrees of nitrogen deficiency result in a retardation of growth. Depending upon circumstances, this may be advantageous or disadvantageous. In the hands of experienced fruit growers, nitrogen manipulation becomes a valuable means of exercising a high degree of control over the quality of growth produced by trees. Control over nitrogen supply results in an indirect control over carbohydrate utilization in the trees, which, in turn, assists in improving bud set, fruit color and winter hardiness. Because of this, nitrogen is sometimes referred to as "the balance wheel in plant nutrition." If other nutrients, water, light and temperature are favorable, tree growth can usually be accelerated or retarded by controlling the nitrogen supply.

A deficiency of nitrogen may occur at any time during the growing season in trees of any age. The symptoms are manifested in various ways according to the part of the season at which the deficiency develops and its severity.

In the spring, when a rapid renewal of growth is taking place, a

deficiency of nitrogen may result in a relatively small set of fruit and be associated with leaves that mature without attaining normal size. Nitrogen deficiency at this stage frequently is overlooked, for the young foliage and twigs do not then exhibit the hard growth condition and pronounced discoloration usually associated with a lack of nitrogen later in the growing season. For the most part, this form of nitrogen deficiency is avoided by early spring fertilization. In general, the deficiency may be foretold the previous summer or early fall by the appearance of symptoms of nitrogen hunger. Compton et al. (5) have established color standards by which the relative supply of nitrogen in McIntosh apple leaves sampled between mid-July and late August under New York conditions can be estimated by comparison with a range of seven green colors.

Through most of the spring and summer, nitrogen deficiency is indicated by a gradual decrease in greenness and associated increase in yellowness of mature leaves. In all instances, the symptoms appear first near the base of the current growth and progress toward the tip. If the deficiency is a severe one, however, as in orchards where it has been allowed to develop over a period of a year or more, or if the trees are young, yellow foliage may appear at the tips of twigs soon after the basal leaves are affected. At the same time, new leaves fail to attain their normal size for the variety, and the leaf stalks (petioles) tend to form narrow angles with the stems. Nitrogen deficiency is associated with a gradual accumulation of carbohydrates and anthocyanin (purple) pigments, and with a general decrease in vegetative activity. Twig growth, therefore, becomes stiff and woody, limited in length and diameter, and reddish or brownish in color. These symptoms are illustrated in plate 1, page 253. Elongation of twigs and spurs stops early.

Trees affected by a mild lack of nitrogen may mature fruits of normal or nearly normal size and good color. When the nitrogen deficiency is very pronounced, fruits become drastically reduced in size and tend to ripen and drop prematurely. Such trees, moreover, are apt to set fruit poorly in the spring.

In some instances, a deficiency of nitrogen may be forecast by the appearance of surrounding vegetation. Where apple trees develop a pronounced deficiency of nitrogen, nonleguminous sod plants, cover crops or weeds in the orchard usually are stunted in size and yellowish in color.

Phosphorus Deficiency

Many cover-crop and sod failures in orchards are caused by insufficient phosphorus. The accumulation of a high degree of acidity in orchard soils is conducive to a low availability of phosphorus to the trees. This condition leads in time to unsatisfactory tree growth. Phosphorus, however, is not required by apple trees in such large quantities as nitrogen, potassium or calcium. Mature apple trees, moreover, may store amounts of phosphorus adequate to sustain apparently normal growth for several years after the soil has become deficient in this element. Such growth is often accomplished by the redistribution of phosphorus from mature tissues to growing parts, where it is used over again. This is attended by the death of many cells and the weakening of others in tissues from which phosphorus is withdrawn, to such an extent that the hardiness of the tree is seriously affected. When the supplies of phosphorus in the tree and in the soil are no longer sufficient to meet the requirements for this apparently normal growth, deficiency symptoms appear.

Nursery apple trees have small reserves of phosphorus and, owing to their relatively rapid growth, are likely to exhibit deficiency symptoms within 2 or 3 months when planted on soils lacking this nutrient.

As the phosphorus supplies of apple trees fail to meet the requirements for growth, the foliage retains a good color, or it may appear somewhat darker than usual. New leaves do not attain normal size, and the twigs—which may or may not be curtailed in linear growth, depending upon the severity of the deficiency—do not reach normal thickness. At the same time branching becomes obviously restricted. Phosphorus-deficient trees, like nitrogen-deficient ones, develop leaves with narrow petiole angles. The petioles and the veins of the lower leaf surfaces may become conspicuously purplish. These symptoms are illustrated in plate 2, page 254. In the early phases of phosphorus deficiency the utilization of sugars appears to be retarded and hence they accumulate. This results in the development of abnormal amounts of anthocyanin pigments, so that, particularly during cool spring or summer weather, all of the current-season growth may appear purplish or purplish red.

If the deficiency is allowed to become severe, the oldest leaves develop a mottled appearance with yellowish-green and dark-green areas. These mottled leaves soon drop. Twig diameter on such

trees is conspicuously small, and fruit-bud formation is seriously reduced.

There is also some evidence of a lack of normal winter hardiness in phosphorus-deficient trees.

Potassium Deficiency

Potassium requirements of apple trees are about as large as or larger than those for nitrogen. Nevertheless, in many commercial orchards the amounts of potassium applied are small in comparison with those of nitrogen. Under such conditions, apple trees are dependent upon the inherent and residual supplies of potassium in the soil. When these fail to meet the requirements for growth, symptoms of potassium deficiency develop. The relative ease with which these symptoms may be identified is dependent upon the severity of the deficiency.

Where the potassium supply of an orchard soil is inadequate to meet the requirements of the trees, this condition is usually indicated in the growth of cover crops. The latter often have high potassium requirements compared with those of apple trees, and consequently may show symptoms of potassium hunger several seasons earlier than the trees grown on the same soil. Both strongly acid soils and soils abundantly or excessively supplied with calcium and magnesium are conducive to the occurrence of potassium deficiency in apple trees.

Trees affected by a mild deficiency of potassium may easily be confused with trees slightly lacking in nitrogen. Indeed, the symptoms exhibited may actually be those of nitrogen deficiency, since it has been found that apple trees lacking adequate amounts of potassium cannot utilize nitrates efficiently. Moreover, in the early stages of potassium deficiency carbohydrates accumulate in the tree. Associated with this is a slightly yellowish-green color of the foliage, and the amount of yellow (or red, depending on the variety) in the twigs also may increase.

In apple orchards in which pronounced symptoms of potassium deficiency have appeared a characteristic type of foliage necrosis (death of tissues), or "scorch," develops after the terminals have made several inches of growth. The first leaves to be affected are those near the middle or slightly below the middle of the current-season growth. From this portion, the injury spreads toward the tips and bases of affected twigs. The areas which later develop scorch are usually located along or near the leaf margins, and first

appear as dark-purplish discolorations as shown in plate 3, page 255. These discolored portions are plasmolyzed areas (that is, cell sap is extruded into the spaces between the cells, giving the tissue a water-soaked appearance) and they usually develop into scorched ones within a few hours or a day during warm summer weather. As a result of the relative inelasticity of the dead areas, subsequent growth in adjoining tissue causes crinkling and curling. The intensity of leaf scorch varies with the severity of potassium deficiency. Thus trees in which potassium is moderately deficient exhibit a type of scorching that is very largely confined to the leaf margins, as shown in plate 3, page 255. When there is a severe deficiency, scorched areas develop throughout the blade tissue, as shown in plate 4, page 256.

The symptoms of potassium-deficiency scorch on apple foliage are shown in plates 3 and 4. The plants from which these illustrations were made were grown in a greenhouse, where it was possible to obtain leaf specimens that were free from spray burning as well as from insect and disease injury. Because of this, the final leaf color developed by the scorched areas was somewhat lighter and brighter than that of leaves found in the orchard. When the scorched areas are exposed to rain in the orchard they assume a dull brown color that is several shades darker than that illustrated.

Following the development of scorch, new leaves fail to attain normal size. This reduction in leaf size becomes more pronounced as potassium deficiency increases in severity.

It is characteristic of the necrotic or scorched leaves of the apple, as well as those of most plants affected by potassium deficiency, to remain attached to the stems or twigs for some time after they have dried up.

Preceding the plasmolysis and purpling, potassium is withdrawn from the affected areas and moved to the growing tips and newly expanding leaves. This transfer and reuse enables trees that are not too deficient in potassium to make as much or nearly as much linear growth as normal trees. The growth produced by the deficient trees, however, is characteristically slender. Moreover, limited observations both in the United States and in England have shown that potassium-deficient apple trees are abnormally susceptible to wilting.

If the deficiency is not too severe, scorched trees may set an abnormally large number of small fruit buds. These buds blossom and set a fair amount of fruit, but owing to the weak condition of

the trees and the reduced leaf area, the mature fruits are abnormally small.

Calcium Deficiency

The role of calcium in the apple orchard is often confused with that of lime. Calcium comprises a large portion of the ash of apple trees and is absolutely indispensable to growing tissues. On the other hand, the fact that productive apple orchards are found on strongly acid as well as neutral soils has led some people to underestimate the importance of calcium in practical fruit growing. For the most part, the occurrence of calcium deficiency is confined to soils having an inherently low supply of the element rather than to those that are strongly acid. The latter condition is conducive to rapid losses of calcium, but, since some acid soils are derived from rocks well supplied with this element, soil reaction alone is not necessarily an indication of the calcium supply. The influence of soil acidity on plant nutrition in general has been discussed in the first chapter of this book. In a few instances, a deficiency of calcium in apple orchards has been induced by the excessive use of potash fertilizers on soils inherently low in calcium supply.

Because apple trees grow to be large plants and because they succeed best on well-aerated soils, they are dependent on the subsoil for much of their moisture supply during the summer season. It is important, therefore, that the trees develop their roots to such a depth and extent that they can procure whatever soil moisture is available during drought periods. For this reason an adequate supply of calcium is very important, since a deficiency has a retarding effect on root growth.

The symptoms of calcium hunger in apple trees usually become evident in the roots before they do in the tops. The extent to which fruits manifest calcium-deficiency symptoms is dependent upon the degree to which the calcium supply is limited. Calcium-deficient roots are abnormally short and stubby. In the case of a mild deficiency the tips of new roots stop elongating early, while the cortex —the outer layers of cells—continues to thicken and new roots emerge in abnormal abundance a short distance behind the tip. When the calcium supply actually fails to meet the demands for growth, apple roots die back from the tips to the old, woody portions. Many new rootlets usually emerge from the live tissues a short distance behind the dead tips. Masses of short, stubby, excessively branched roots, as illustrated in figure 1, are indicative of calcium deficiency.

Symptoms of mild calcium hunger may be exhibited by apple tree roots without the occurrence of distinctive deficiency characteristics in the top, although the growth of affected trees becomes retarded. This form of calcium deficiency occurs more frequently than that associated with foliage necrosis. Inasmuch as the roots of apple trees may be expected to reveal symptoms of calcium deficiency soon after such a condition develops in the soil, root growth is a more reliable index of the adequacy of calcium supply than is top growth.

Figure 1.—Symptoms of calcium deficiency in apple roots. Roots tend to be somewhat bulbous, and usually die back from the tips after making a short growth.

If young trees are planted in a soil very deficient in calcium, they may make several inches or a foot of growth and then form terminal buds. The foliage on these trees may show none of the specific symptoms of calcium hunger but may appear relatively normal except for a reduction in size. This has occurred repeatedly under experimental conditions and has been observed to occur in orchards. Calcium is required primarily in regions of new growth, and it is not transferred in significant amounts during the growing season from old to new tissue. Thus there may be considerable amounts of calcium compounds present in mature portions of plants whose tip growth has been inhibited by a lack of calcium. During the dormant season, some supplies of calcium are liberated in a soluble form by the break-down (hydrolysis) of previously insoluble calcium compounds in mature tissues and by the death of some cells. The liberated calcium is available for new top and root growth the following spring.

After several inches or a foot of new twig growth has formed, discolorations and necrotic areas develop on the young leaves (plate 5, page 257). The tips and sometimes the margins of affected young leaves may curve downward. Injury to the tip leaves is soon followed by the appearance of areas of dead tissue on nearly mature leaves that are still growing. Death of the discolored areas of leaf tissues is preceded by the development of light-green areas that usually turn a dull dark brown in a day or two.

When young apple trees are planted on soils which, although lacking an adequate supply of calcium, provide very limited amounts to the roots, the symptoms of deficiency are the same as those just described for young trees in their second season.

The supplies of calcium available to the growing twigs of mature apple trees are depleted only gradually. Consequently the rather sudden arresting of growth described for newly planted apples is not likely to occur.

Magnesium Deficiency

The soils of many commercial apple orchards in parts of New York and New England are now known to contain too little magnesium to meet the requirements of the trees. Although a lack of magnesium is most apt to be encountered in light soils that are acid it also occurs on heavy soil. In orchard soils inherently low in magnesium, the continued use of potash fertilizers has been found conducive to the development of magnesium deficiency. Similarly lack of adequate magnesium has been associated with the use of relatively large amounts of nitrate of soda or high-calcium forms of lime. This deficiency is especially favored by heavy, leaching summer rains.

Symptoms of magnesium hunger are very distinctive. When the deficiency first develops and before any foliage necrosis occurs, leaves have the lush, dark-green color of trees abundantly supplied with nitrogen. With young, rapidly growing trees on light soils, this stage is often accompanied by the appearance of chlorosis on the young terminal leaves. Later, mature leaves near the base of the current season's growth develop light-green or grayish-green blotches between the veins. These blotches frequently extend to the leaf margins, although they may occur near the middle of the blades. The light-green or grayish color on any leaf seldom lasts more than a few hours or half a day before turning a fawn color and then a dark brown. This may be followed in a day or two by

the shriveling and falling of affected leaves. The effect of magnesium deficiency in defoliating 1-year-old apple trees is illustrated strikingly in figure 2. The defoliation progresses rapidly toward the terminals until only a rosette of soft, thin, light-green leaves may remain. Progressive stages of leaf blotching caused by magnesium deficiency in mature twig foliage are shown in plate 7, page 259. A large portion of the magnesium in the affected or blotched

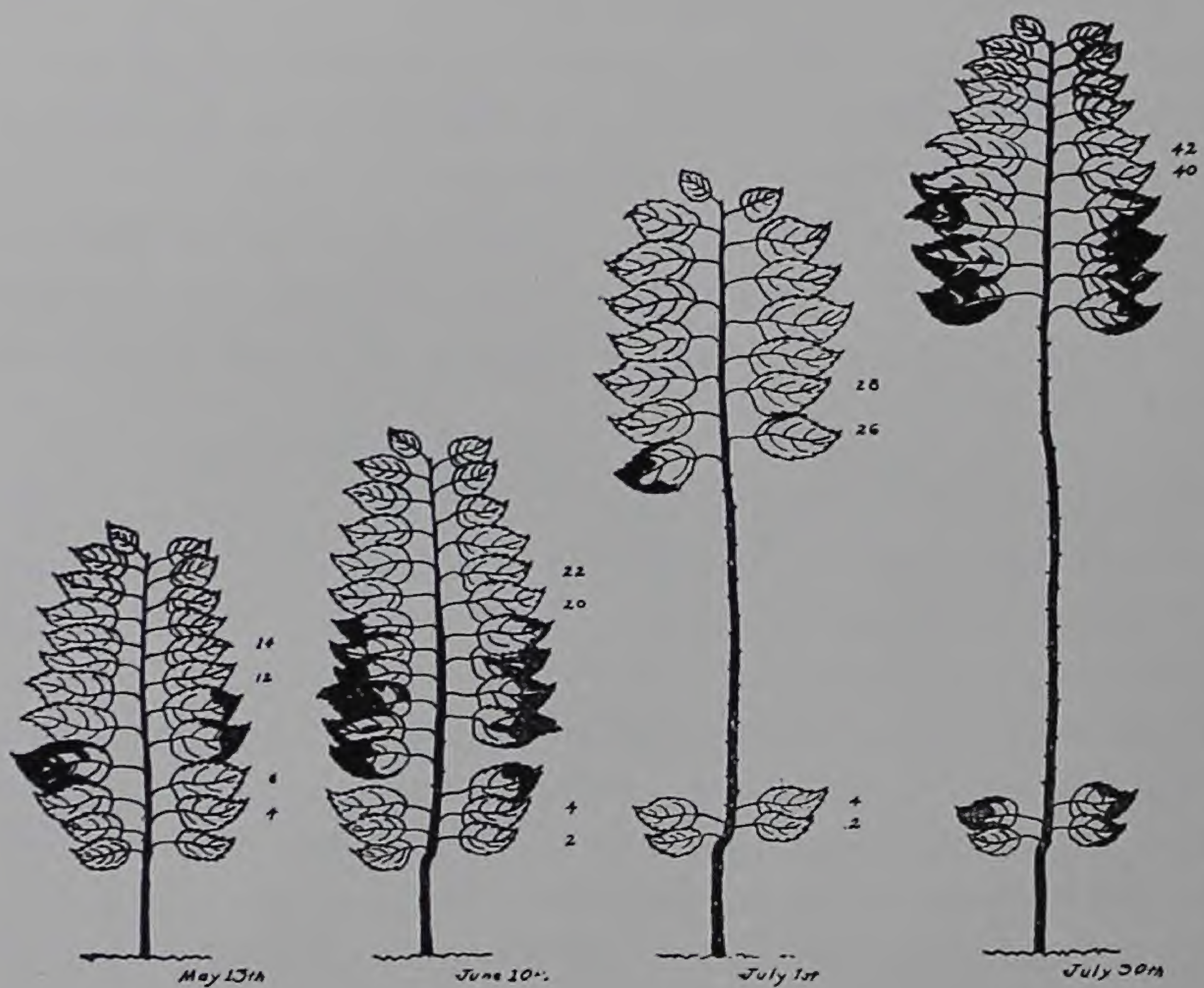


Figure 2.—Diagrammatic illustration of progressive leaf fall as a result of magnesium deficiency on 1-year-old apple trees. Black areas indicate blotched portions of leaves.

leaves is translocated to the growing tips. This enables growth to continue even on trees that show severe defoliation.

In mature apple orchards lacking adequate magnesium, symptoms of the deficiency are apt to occur during late July or in August. The blotched leaves on these trees are not so apt to drop soon as are affected leaves on young apple trees. Spur leaves as well as twig leaves may develop blotch. Since leaves as well as magnesium are essential to carbohydrate manufacture by trees, the defoliation and blotching that accompany magnesium hunger result in a soft type of growth. Fruits on such trees, therefore, are abnormally small, and poor in color and in edible quality. Experience with 1-year-old trees, moreover, indicates that magnesium deficiency greatly reduces their resistance to winter injury.

Boron Deficiency

The soils in many apple-growing regions are deficient in boron unless this nutrient is added by fertilizers or is sprayed on the trees. A lack of this so-called minor element is apt to cause serious loss in commercial apple orchards. Various types of boron deficiency have been given descriptive names by growers and investigators. "Drought spot," or external cork; "corky core," or internal cork; and "drought dieback" in apple trees are known to be due directly to boron deficiency.

Boron deficiency occurs on a wide variety of orchard soils. It is found on limestone soils, on acid soils, on sandy soils, on stony soils in hilly regions, on dry soils, and on excessively wet soils. In regions affected by the deficiency, it is most common during dry years. Applications of nitrogen, by increasing the growth of apple trees, also increase the boron requirement, thereby augmenting the deficiency. It has been shown also that in some regions excessive liming, especially on strongly acid soils, is conducive to the development of this trouble.

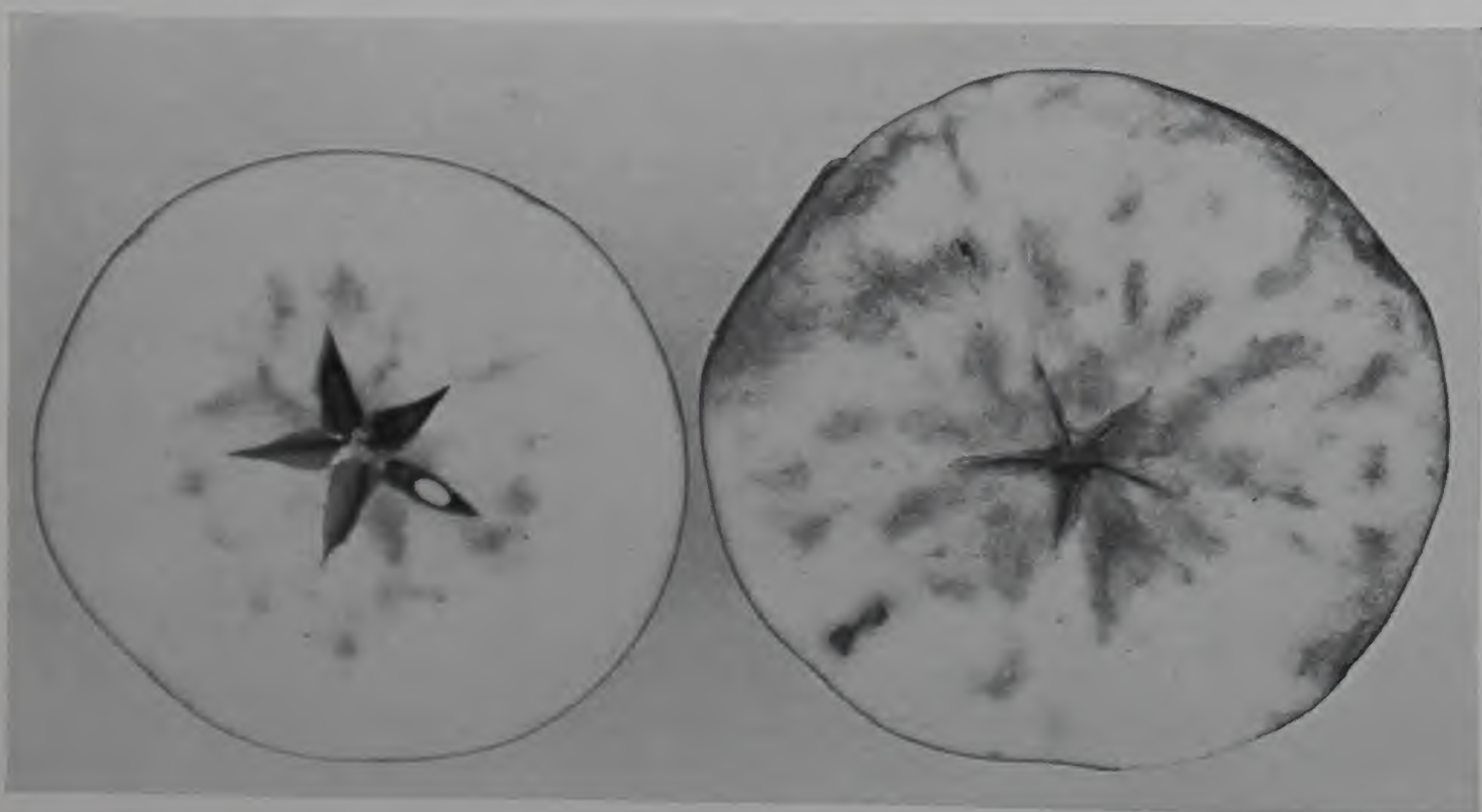


Figure 3.—Symptoms of boron deficiency in apples: Internal cork in McIntosh fruits. This type of boron deficiency usually develops during the late summer.

As long as any part of an apple tree is growing, it needs a continuous supply of boron. This nutrient is not stored in the plant tissues and transferred to regions of new growth as is the case with some other nutrients. Because of this, a deficiency of boron may develop at almost any time during the growing season. Moreover,

the ailment may develop for the first time in either a mild or a severe form. It may be manifested one year by one group of symptoms and another year by a different group. Thus it is not uncommon for a tree to develop internal cork on the fruit one year and external cork the following year.

Internal cork may develop in the fruit on boron-deficient trees any time from 2 weeks after petal fall until harvest. Roundish water-soaked areas develop in the flesh and change quickly to brown-colored lesions which dry and become corky. These areas may develop anywhere throughout the flesh. When internal cork develops early in the growing season, the affected fruits become deformed and tend to drop badly. Apples developing internal cork late in the season show larger and more diffused brown lesions, but they are not misshapen. McIntosh fruits affected by late internal cork are illustrated in figure 3. The brown lesions developed in mature fruits may have a decidedly bitter taste, the apples mature early and drop prematurely, and red varieties often show more or less bronzing.

External cork always develops early in the growing season and may appear within 2 weeks after petal fall. The first symptom is the occurrence of water-soaked, dead areas of the surface of the young fruits. Although these areas may appear on any portion of the fruit, they are most apt to occur on the inner or green side. The lesions become brown and hard, and, since they are on the surface, subsequent growth of the fruit causes cracking, wrinkling and scurfing of the skin, as shown in figure 4. Affected fruits may drop when they are little more than an inch in diameter or they may

Figure 4.—External cork in McIntosh fruits at harvest time. This type of boron deficiency usually develops within 2 weeks after petal fall.

Courtesy of A. B. Burrell, Cornell University

adhere to the trees. Fruits that are only slightly affected may attain normal size.

According to A. B. Burrell (2), when a serious deficiency of boron develops within 8 weeks of petal fall, it is usually manifested in the fruit as external cork in the McIntosh, Baldwin, Rome, Northwestern Greening and Jonathan varieties. With the varieties Fameuse, Ben Davis, Cortland and Rhode Island Greening, the external type of cork develops at the surface and remains intact. On the other hand, the varieties Wealthy, Duchess of Oldenburg and Spy, when affected by the deficiency at this time, develop both the external and the internal types of cork, as shown in figure 5. Burrell has found that, regardless of the variety, cork developing more than 8 weeks after petal fall is usually manifested as the internal type.

Although the losses to apple growers from boron deficiency have been due mainly to direct injury to the fruits, considerable damage sometimes occurs to the vegetative portions of the trees. Injury to the wood may be due to boron deficiency alone, or to a combination of its direct effects and winter injury caused indirectly by the reduced vigor associated with the deficiency.

Burrell (2) has described three types of boron deficiency in apple twigs and leaves in the Champlain Valley region of New

Courtesy of A. B. Burrell, Cornell University

Figure 5.—Oldenburg apples about 5 weeks after petal fall, showing symptoms of both internal and external cork due to boron deficiency.

York State. The first of these, known as "incipient dieback," appears on twigs in the late summer. Leaves on current-season twigs affected by this form of boron deficiency appear yellowish with red veins and are somewhat convex and otherwise distorted in shape. Necrotic areas subsequently develop at the tips and margins. A distinctive symptom of incipient dieback is the occurrence of small necrotic areas in the phloem and cambium tissues (bark, and tissue between bark and wood) near the twig tips. Burrell reports that this necrosis is found especially under axillary leaf buds. The enlargement of these areas results in death of the twigs from the tips downward.

Courtesy of A. B. Burrell, Cornell University

Figure 6.—Rosette and dieback of McIntosh apple tree caused by boron deficiency. Leaves are narrow, thick, and have smooth rather than serrated margins.

A second type, known as "dieback," has been found in boron-deficient orchards in New York State and in the Provinces of New Brunswick and British Columbia. The first indication of this form of deficiency may be observed in the spring when otherwise normal buds fail to develop or make a delayed and feeble growth and soon die. Affected twigs may die back from their tips to wood that is several years old. Subsequently, an abnormal number of small twigs may branch out from wood just below the dead portion. These new branches may soon die back in a similar manner and tend to stimulate the development of another set. This process gives rise to an excessively branched condition often known as "Witch's broom," which is also common in boron-deficient roses and tomatoes. Boron deficiency of this type may kill an apple tree in a few years.

Another form of boron hunger is manifested by the production of dwarfed, thickened and brittle leaves arising from nodes separated by abnormally short internodes. The effect produced is that of a rosette of leaves, and hence Burrell has applied the term "rosette" to this form of the deficiency, which also occurs in roses and other plants. Burrell has made the interesting observation that the rosette leaves have smooth rather than serrated margins. Rosette and dieback may develop on the same branch, as shown in figure 6.

Zinc Deficiency

The growth of apple trees is seriously curtailed by a lack of zinc in a number of different fruit-growing regions in the United States, and on vastly different soil types. In some of the sandier areas it seems likely that the zinc supply of the soil may be depleted, but in some other regions this has not occurred. It is known, however, that some soils have a high capacity for zinc fixation, which may possibly account for the development of zinc deficiency in trees grown on them. The deficiency is responsible for rosette of apple and pecan trees, "little leaf" of stone fruits and grape fruits, "mottle-leaf" of citrus, and "yellows" of walnuts. The symptoms of zinc deficiency in these various fruits show marked similarities.

Apple rosette, caused by zinc deficiency developing in the spring, is characterized by whorls of small, stiff and sometimes mottled

Figure 7.—Symptoms of zinc deficiency in apple. Branch on left shows normal growth a year after treatment with zinc sulfate. Branch on right was not treated with zinc sulfate and shows dieback, rosette and small foliage due to zinc deficiency.

Courtesy of H. W. Ridgway, Hampton Institute

leaves near the tips of current-season twigs. Many of the leaves, in fact, may be no more than an inch in length and a quarter inch in width. Except for these terminal rosettes, the twigs may be bare for some time. Following this, branches arise from below the affected twigs; these usually produce leaves that are nearly normal early in the season but later become mottled and misshapen. Fruit-bud formation is severely reduced, and the fruits that develop are usually small and malformed. Twigs may begin to die back after the first year.

Less severe types of zinc deficiency are associated with the formation of prominent rosettes of small, narrow, chlorotic or mottled leaves after twigs have grown several inches. Most of the leaves formed before the development of the rosette tend to drop off. Twigs are spindling and short. Few fruit buds are formed on affected branches. Just as in severe cases, branches arise from below the affected twigs and produce fairly good leaves. These symptoms are illustrated in figure 7.

PEACHES

Nutrient deficiencies are somewhat more common in peaches than in apples, owing primarily to three factors: (1) Peaches are frequently grown on soils that are lighter and inherently less fertile than those ordinarily used for apples. (2) In general, peach trees, especially young ones, grow at a faster rate than do apple trees. Moreover, they normally continue rapid growth for a longer period than do apple trees. Other things being equal, the nutrient requirements of a plant increase in proportion to its rate of growth. (3) Peach trees are poorer competitor plants than are apple trees; consequently they soon show signs of starvation when crowded by weeds or cover crops on inadequately tilled soil.

It may be indicated at this point that peach trees on very light, sandy soils may be prone to exhibit symptoms of nitrogen deficiency periodically even when well fertilized with nitrogen. When soil moisture is not provided in adequate amounts the utilization of nitrogen by trees is inhibited. Likewise, peaches on very acid soil may make an unsatisfactory growth except when abnormally large amounts of fertilizer are used, and even then, in some instances, they may grow poorly. When endeavoring to account for unsatisfactory growth of peach trees, these limitations must be considered.

Nitrogen Deficiency

In peach orchards, deficiency of nitrogen occurs more commonly than that of any other nutrient. The symptoms of pronounced nitrogen hunger are familiar to commercial peach growers, for even on relatively good soil the trees may develop the symptoms within a very short time if they are forced to compete with weeds on untilled or inadequately tilled land. Indeed, unless special precautions are taken, as for example mulching and frequent applications of nitrogen fertilizers, it is sometimes difficult to prevent the development of nitrogen deficiency in peach trees grown in sod. Likewise, where young, rapidly growing peach trees are planted on light, sandy soils, symptoms of nitrogen deficiency may occur within a few days after heavy leaching rains in late May and June. It is important that the symptoms of nitrogen deficiency are readily recognized, for prompt and appropriate attention usually corrects the deficiency before any substantial damage is done to the tree. On the other hand, a delay of two weeks may seriously reduce growth and yield and may weaken young trees.

In the initial stages of nitrogen deficiency, mature leaves located near the bases of current-season twigs gradually become yellowish green and then greenish yellow. This is followed by a retardation of growth and a readily discernible stiffening of growing shoots 2 to 4 inches behind their tips. These symptoms may appear very quickly. If the deficiency continues to develop, leaves become yellowish green progressively from the bases to the tips of current growth. Simultaneously, twigs become spindling, short and stiff, with brownish-red or purplish-red bark.

Nitrogen is translocated from mature or slowly growing tissues to regions of active growth. Consequently, the deficiency symptoms may develop to a pronounced degree on the older and lower twigs of a peach tree while well-exposed upper branches show only mild symptoms.

When linear growth on short twigs is checked considerably or when the young leaves on long current-season twigs are yellowish and fail to attain normal size, nitrogen deficiency in the old leaves is acute. Leaf color at this stage varies from yellowish green at the tips of growing twigs to reddish yellow at the bases, where red and brown spots characteristically develop. Depending upon the activity of the twigs and the location of the leaves, foliage will vary in color from yellowish green, through greenish yellow and yellow, to reddish yellow. Red spots or necrotic brown spots

are common on all but the yellowish-green leaves, and some may be found on these. Leaf discolorations characteristic of nitrogen deficiency are illustrated in plate 8, page 260.

When nitrogen deficiency in peach trees reaches the stage at which reddish, spindling twigs with red-spotted leaves are found, fruit-bud formation may be severely curtailed. In fact, any deficiency of nitrogen that causes a reduction in twig growth is apt to decrease fruit-bud formation. Moreover, the winter hardiness of both twigs and buds may be reduced. Fruits formed on branches producing these twigs are usually small and abnormally astringent for the variety. With red varieties the color may become dark and unattractive.

Phosphorus Deficiency

Lack of adequate phosphorus is responsible for considerable losses to peach growers each year. A deficiency of phosphorus is particularly serious in young and replanted peach orchards, where a lack of this nutrient reduces the vigor of the trees to such an extent that losses during the first winter are often very high. Where the soils are low in phosphorus, cover crops fail or make only poor growth. This condition results gradually in reduced vigor in the trees and decreased longevity for the orchard. Acid soils, light sandy soils, soils particularly low in organic matter, as well as those having a high capacity to adsorb phosphorus, are apt to supply too little of this nutrient to meet the needs of cover crops or trees in peach orchards.

Since phosphorus can be reutilized in peach trees, symptoms of an inadequate supply would be expected to appear first on the old leaves of current-season twigs. While this is apt to be the case, characteristic symptoms also appear on young foliage at about the same time. At the onset of deficiency symptoms peach foliage, young and old, attains a dark-green color that might cause it to be mistaken for that of a tree well-fertilized with nitrogen. If the prevailing temperatures are rather cool at this time, careful observation should reveal a purple or bronze pigmentation on the veins of the lower leaf surfaces and on the petioles. Regardless of temperatures, this stage is followed by a bronzing and tanning of the upper leaf surfaces, as illustrated in plate 10-A, page 261. Moreover, if cool weather prevails during this stage, the leaves will show more or less reddish or purplish pigmentation, especially along the margins of blades and on leafstalks.

Associated with the bronze or tan discoloration on the foliage, the uppermost new leaves tend to become more erect than usual, while those just below the tip stand out approximately at right angles to the twigs. The leaves characteristically curve downward near the margins and at the tips; this is shown in plate 10-B. In general, the newly matured leaves do not attain normal width.

At about the same time that changes occur in the conformation and position of leaves at the tips of current-season twigs, mottling develops on foliage at the bases of twigs and progresses upward. In some respect this mottling is not unlike that which may normally precede the dropping (abscission) of basal leaves. The mottling shown in plate 10-C, page 261, however, is characteristic of phosphorus-deficient peach trees and may appear weeks or months in advance of abscission, depending upon the degree to which the nutrient is lacking. Instances have been observed in which peach trees deficient in phosphorus lost nearly all leaves except those near the tips of twigs. Afterward, the trees renewed their growth and developed leaves which, although they showed symptoms characteristic of phosphorus hunger, held through most of the season.

Peach trees only slightly lacking in phosphorus may make a fair growth, but they develop relatively few branches. The latter, moreover, are rather slender. If the deficiency is severe, whorls of leaves form at the tips of twigs after little more than a quarter of the normal growth has been produced.

Potassium Deficiency

Peach trees have a relatively high requirement for potassium and consequently are apt to develop symptoms of potassium hunger unless the soil is adequately supplied with this nutrient, either from its inherent mineral content or from applied fertilizers. Peach trees may show symptoms of potassium deficiency in the same orchard where apples show little or no definite evidence of a lack of this nutrient. This is probably due to the fact that peaches usually require as much if not more potassium than do apples, and also because their period of rapid growth is normally longer than that of apples.

Potassium deficiency occurs in commercial peach orchards planted on light sandy soils, droughty shales, limestone soils, acid soils, soils with high potash-fixing or adsorbing capacity, and also on soils that are for one reason or another abnormally low in organic-matter content. On light sandy soils, potassium deficiency

can be induced in peaches by excessive applications of lime. Although the lime may have a beneficial effect on the soil and ultimately on the trees, heavy applications are apt to reduce the availability of potassium to the trees (6). The use of nitrogenous fertilizers on soils that are slightly deficient in potassium is apt to stimulate growth of the trees to such an extent that the supply of potash is no longer adequate.

The first diagnostic symptom of potassium hunger in peach trees is the development of crinkled leaves near the middle portion of current-season twigs. The crinkling is caused by uneven growth of blade tissue, and is particularly noticeable along the midrib. As the deficiency increases in severity the crinkling becomes more pronounced and more extensive over the tree, and is often associated with more or less rolling of the leaves, as shown in figure 8. The rolling is apt to develop particularly during dry weather. This may be an adaptation to reduce transpiration, since it has been shown that potassium-deficient trees are particularly subject to wilting. The rolling of peach leaves due to potassium deficiency is always associated with crinkling and curling of the blade tissues. This type of rolling should not be confused with that caused by some stages of calcium deficiency, by cold injury, by girdling, and by some other translocation abnormalities that cause rolling without crinkling.

Figure 8.—Crinkling and curling, together with some rolling of leaves, preceding the development of foliage necrosis on a potassium-deficient peach tree grown in sand culture.

Simultaneously with the appearance of crinkling, peach trees may exhibit some of the symptoms of nitrogen deficiency. This is because a deficiency of potassium restricts the utilization of nitrogen in the plant. The twig tips tend to stiffen, and the leaves acquire a yellowish-green color that is more prominent with the yellow-fleshed than with the white varieties. This stage is usually fol-

lowed by the development of small straw-colored areas of dead tissue in the leaf blade (see plate 11-E, page 262). These areas may remain small and straw-colored for a few days or they may expand into larger areas that become brown. These stages are illustrated in plate 11-F. The necrotic areas are usually bordered by definite lines, or abscission zones, which, in the field, are often discolored reddish brown or purplish red. The dropping out, or abscission, of many of the necrotic areas in the blades and along the margins leaves holes—not unlike those formed by the "shot-hole" disease of peaches—and scalloped edges. Careful examination will usually reveal dark-green, water-soaked (plasmolyzed) areas that are the initial stages of necrosis in the blades. The withdrawal of potassium from these areas and its reutilization at the growing tips are sometimes followed by an improvement in the color of immature and recently matured leaves, and an increase in rate of growth. Leaves maturing throughout the remainder of the season fail to attain normal size, especially in length. Young peach trees in a greenhouse have been observed in a single season to undergo three successive cycles of leaf necrosis followed by renewal of growth. The first cycle was the most pronounced of the three.

If potassium is supplied to and absorbed by the affected trees at this stage they utilize it readily, as might be supposed from the fact that they quickly reutilize the potassium withdrawn from necrotic leaves. Necrotic areas in mature foliage may continue to develop, however, for several weeks after potassium has been supplied to the trees, even though tip growth is rapid and normal.

In orchards lacking adequate potassium, the deficiency symptoms increase in severity throughout the growing season. Areas of dead tissue along the leaf margins, particularly, become increasingly prominent. The affected foliage also develops cracks and tears as a result of the action of wind on the inelastic dead areas. At the same time, light-red or purplish-red pigmentation develops on affected leaves, especially on the exposed lower surface of the longitudinally rolled blades.

Unlike nitrogen- or phosphorus-deficient leaves, the tattered and discolored leaves on trees lacking potassium adhere to the twigs for a long time. If active growth is renewed after considerable foliage necrosis has occurred, the affected leaves may drop off prematurely. Likewise, if the deficiency develops in the early summer and continues throughout the season, many leaves may fall early. On the other hand, when the deficiency symptoms first develop

rather late in the season, the affected leaves usually adhere until normal leaf fall occurs, or even later.

As a consequence of the reutilization of potassium in peach trees, linear growth of deficient trees is not always greatly curtailed. In fact, trees exhibiting only the mild deficiency symptoms may make nearly as much growth as those abundantly supplied with potassium. The twigs on deficient trees, however, are usually slender.

The effects of potassium hunger on peach fruit-bud formation are most severe. Even in relatively mild cases, when only a small portion of the foliage develops necrosis and little defoliation occurs, the trees may fail to form a single fruit bud. If the deficiency symptoms do not appear until late in the summer, fruit buds may form, but only on the most vigorous twigs, and yields consequently are very small.

If potash is not supplied to peach trees that developed symptoms of a severe deficiency during the previous season, dead areas may appear on newly expanding foliage at the time at which growth is renewed in the spring or very shortly thereafter. In this case, the necrosis may occur with or without crinkling of the foliage, as shown in plates 11-A and -B, page 262.

Calcium Deficiency

Peach trees may lack adequate supplies of calcium irrespective of the pH values of the soil on which they are growing. The excessive use of potash fertilizer or nitrate of soda on light soils inherently low in calcium may induce a deficiency of the latter. Nevertheless, peaches growing on such soils require considerable nitrogen and potash, efficient use of which is dependent upon an adequate supply of calcium.

Calcium hunger in peaches, as in most other plants, is revealed very quickly by its effect on root growth. New roots are abnormally short, thick and crooked. Most of the roots die back from their tips after making a growth of ½ inch to 3 inches. Moreover, there is a very pronounced and characteristic tendency for new roots to arise in profusion a short distance behind the tips of deficient roots (figure 9). Although a few roots may make a fair amount of growth, root extension in general is drastically curtailed.

If peach trees are suddenly subjected to a lack of calcium, as when young peach trees from a nursery are planted in a soil deficient in this nutrient, they may show signs of wilting for a

period of about a week after they have completed a month or more of growth in the spring or early summer. This period of wilting coincides with extensive dieback of the new roots. Mortality at this time may be high. Trees that survive, however, soon become extremely resistant to wilting. In fact, some will stand transplanting in midsummer and show no signs of wilting.

Unlike calcium-deficient apple trees, the tops of peach trees reveal characteristic symptoms of inadequate calcium rather early. Two different manifestations of calcium deficiency in peach tops are common. The severity of the deficiency and the time during the growing season at which it begins appear to be determining factors. (1) If the deficiency starts in the spring or if it is severe at any time during which the trees are making rapid growth, it will be exhibited by necrosis of leaves and twigs. (2) If it develops late in the season when the trees are not growing rapidly, necrosis may not occur in the tops, but the roots may be injured.

Figure 9.—Symptoms of calcium deficiency in roots of a 1-year-old peach tree. Roots are short, sometimes bulbous, and die back after making comparatively little linear growth. New roots emerge profusely behind the dead root tips.

When the supply of calcium in a peach tree fails to meet the requirements of rapidly growing tissues, the first pairs of leaves near the bases of young growing twigs 4 to 8 inches long develop red or purplish-red discoloration along the margins and at the tips. This is followed by some loss of chlorophyll and by necrosis in the discolored areas and then by dropping of the affected leaves. These symptoms are illustrated in plate 12-D, page 263. Only immature basal leaves are affected; those on long twigs remain apparently normal.

Usually the deficiency then follows one of two different patterns. In both cases, the immature leaves develop reddish-brown or dark-brown necrotic areas along the midribs and at the blade tips,

similar to those illustrated in plate 11-C. These areas expand in size, and in one type of manifestation the defoliation progresses toward the midportions of twigs both from the bases and from the tips (plate 12-B). The defoliated twigs die back for only a few inches. In the second type of manifestation, in which there is a greater deficiency of calcium, twig tips and young leaves are killed as by a blight, and the necrosis progresses rapidly down the twigs and affects all immature and some apparently mature leaves. An early stage of this is shown in plate 12-A. Many of the twigs die back to their bases, and some of the branches supporting them die. Below the outermost 2 or 3 inches on each twig, necrosis and discoloration of leaves are similar to those described for the first type of defoliation.

Figure 10.—Longitudinal rolling of leaves on calcium-deficient peach tree.

Previous to the development of foliage necrosis, calcium-deficient peach trees form an unusually large number of big leaves.

It is evident that a bad case of calcium deficiency developing early in the growing season may very seriously injure peach trees, especially those newly planted. Fortunately, however, a deficiency of such magnitude seldom, if ever, affects mature trees. They would necessarily exhibit symptoms of mild calcium deficiency for at least one or more seasons, and this condition could be corrected before becoming more acute.

When calcium deficiency develops rather late in the growing season, or when this nutrient becomes slightly deficient a month or two after the renewal of growth in the spring, linear extension of twigs is gradually restricted. Many twigs become abnormally thickened, especially near the tips. Foliage remains dark and somewhat tannish green rather than normal green. Although the leaves do not grow to a larger size

than is normal for the variety, an unusual number of large leaves develop. Fruit-bud formation starts early in the season, and conspicuously large buds are present in abundance toward the end of summer. Lenticels (pores on the stems) enlarge and become unusually prominent, resembling those on girdled trees. On some trees, the leaf blades roll longitudinally, as shown in figure 10. The tendency for the leaves to roll in this manner is not peculiar to calcium-deficient trees but appears to be associated in some way with restricted translocation of foods.

Magnesium Deficiency

After heavy summer rains, magnesium deficiency occasionally develops in peach orchards grown on light sandy soils. In New Jersey the deficiency has been found during wet seasons in trees grown on very acid loams and on sandy loams that received heavy applications of oyster-shell lime—a high-calcium form of lime that contains no more than a trace of magnesium. On soils that are relatively low in magnesium, a deficiency of this nutrient may be induced by the use of fertilizers containing potassium or sodium. In fact, the occurrence of magnesium deficiency in peach orchards as well as apple orchards appears more likely to be associated with the application of fertilizers containing potash or sodium than it is to be caused by a depletion of the magnesium supply of the soil.

Although magnesium is readily translocated and reutilized in the peach, small and large 1-year-old trees may develop symptoms of the deficiency at about the same time. In all cases observed, both in greenhouses and in the field, mature leaves in the initial stages of the deficiency appear dark green—in some instances, blue green. Leaves near the tips of growing twigs sometimes become slightly but definitely chlorotic. All leaves formed thereafter are abnormally thin. Leaf size, however, may not be affected.

When the supply of available magnesium in the soil fails to meet the requirements for new growth, dark-green, water-soaked blotches appear on the lowermost leaves on large current-season branches, or on the main stems of 1-year-old trees. The pattern of this blotching and the purplish-red discoloration bordering the necrotic areas are shown in plate 9, page 260. Within a few hours the dark-green blotches may change to gray white or green white and then to a fawn color. The latter does not change unless exposed to rain, after which it becomes a medium brown. Within a few days the blotched leaves drop.

In the field, defoliation often continues until nearly half the current growth is bare. In greenhouse studies, however, it may continue until only immature, terminal leaves are left (figure 11). Twigs on such trees become abnormally flexible.

In New Jersey most peach trees that lose many leaves as a result of magnesium deficiency during their first season in the orchard fail to live through the winter.

In fruit-growing regions where magnesium deficiency has been found in mature peach trees, fruit-bud formation has been drastically reduced.

Figure 11.—Normal and magnesium-deficient peach trees grown in sand culture. The magnesium-deficient tree on the right made nearly as much linear growth as the normal tree, but was practically defoliated by late August.

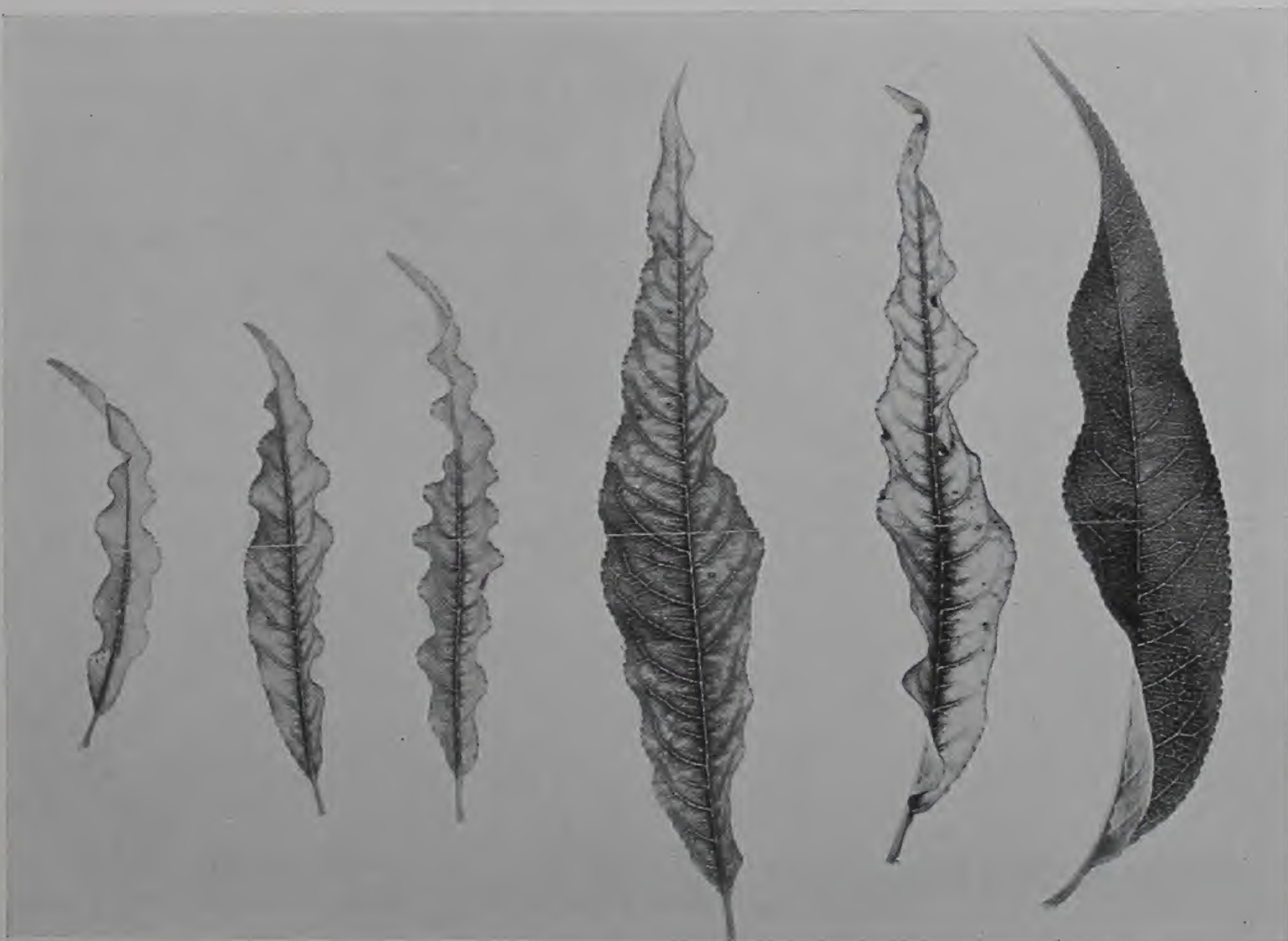
Zinc Deficiency

In parts of Florida and California, zinc deficiency has caused serious losses in peach orchards. The ailment in those regions has been called "little leaf" because of the characteristic rosettes of small leaves that form on the terminals of badly affected trees.

When zinc deficiency develops in a peach tree for the first time, it is manifested as a chlorotic mottling in the foliage late in the summer. This chlorosis progresses upward from the lowermost leaves to those at the tips of twigs. Although 1-year-old trees may

exhibit these symptoms, the trees are usually 2 years old or older before the deficiency develops.

Unless zinc is supplied to these trees, symptoms characteristic of the deficiency will be exhibited the following spring or early summer. Chlorotic leaves appear with yellow-green areas between veins. As the leaves mature, these areas become light yellow, and some develop purple-red pigmentation. Necrotic areas appear at the tips and in the blades of badly mottled foliage. This foliage drops prematurely and often leaves the twigs entirely bare.



Courtesy of R. D. Dickey and G. H. Blackmon, Florida Agricultural Experiment Station

Figure 12.—Crinkling, waving and chlorosis of Jewel peach leaves as a result of zinc deficiency in a Florida orchard. Leaf at right is normal.

At the terminals of twigs, crinkled and chlorotic foliage such as that shown in figure 12 may develop. On the other hand, when the deficiency reaches the stage at which considerable defoliation occurs, rosettes of small leaves are formed at the terminals (figure 13). In severe cases, the leaves in these rosettes may be nearly sessile (without leafstalks), very small, and abnormally rigid. Figure 13 also shows the formation of new twigs below the stunted terminals. Such trees are usually late in renewing growth the following spring. Twigs that fail to develop foliage die back for more

or less indefinite distances, as shown in figure 13. The trees usually die within 3 or 4 years after the onset of the deficiency.

Although fruit-bud formation on zinc-deficient peach trees may be drastically curtailed, some buds usually develop. Very few fruits are produced, however, and those that set on badly affected branches are misshapen and worthless.

Figure 13.—Characteristic symptoms of acute zinc deficiency in young Jewel peach tree in Florida: "Little leaf," crinkling, rosette, defoliation and twig dieback.

Courtesy of R. D. Dickey and G. H. Blackmon, Florida Agricultural Experiment Station

Boron Deficiency

Boron deficiency in peach trees has been recognized only rarely. It has occurred, however, in commercial orchards in the Northwest and it has been developed experimentally in sand cultures.

The symptoms of boron deficiency in peach trees resemble those in apple trees. Twigs on affected trees die back from their tips, but tend to develop new shoots in abnormal numbers behind the injured terminals. Young and immature leaves fail to attain nor-

mal size but become thick, wrinkled and otherwise misshapen and brittle.

Compound Deficiencies in Peach Trees

Although marked stunting of growth may occur when peach trees are grown on soils deficient in two or more basic (or metallic) nutrients, such as potassium, calcium or magnesium, it is very rare indeed for a tree to exhibit diagnostic symptoms of more than one such deficiency at a time. In fact, trees planted on such soils, because of their abnormally slow growth, sometimes fail to exhibit specific deficiency symptoms until they are fertilized with one of the nutrients of which there is a shortage. When attempts have been made to create in sand cultures a deficiency of both potassium and calcium, peach trees have grown very slowly. It was not uncommon to find one tree exhibiting symptoms of calcium deficiency at the same time that a neighboring tree, receiving the same treatment, showed definite symptoms of potassium deficiency. From these studies and from orchard observations it has been concluded that when there is a shortage of two or more basic nutrients in a soil at the same time, deficiency symptoms are apt to be developed only for the nutrient that is most needed in the tree.

Experience with peach trees grown in soils and in sand cultures in which both nitrogen and phosphorus were deficient has shown that, because the former is needed in much greater amounts than is the latter, nitrogen deficiency usually limits growth before the reserves of phosphorus in the tissues are exhausted. An exception to this statement will be described presently.

A similar situation usually exists where nitrogen and some one of the basic nutrients are deficient in the soil. A lack of nitrogen is exhibited by the tree and limits growth before the reserves of other nutrients in the plant tissues are exhausted.

A deficiency of phosphorus, on the other hand, may coexist with that of one of the basic nutrients—potassium, calcium or magnesium. This, in fact, is likely to occur in peach orchards in which either potassium or calcium is deficient. Growers who do not fertilize with potash seldom use phosphates on the trees. Moreover, in acid, calcium-deficient soils the amounts of available phosphorus present are apt to be very low indeed. It has been repeatedly observed and adequately substantiated that, when a compound deficiency of phosphorus and one of the basic nutrients develops in peach trees, the distinctive symptoms of one deficiency are superimposed upon those of the other. In most cases, however,

the symptoms for one nutrient developed before those for the second. The symptoms exhibited are so distinct as to cause little confusion.

Compound Phosphorus-Potassium Deficiency

In New Jersey, a compound deficiency of phosphorus and potassium is second only to that of nitrogen in frequency of occurrence. In some orchards, the symptoms may be those of typical phosphorus hunger with occasional leaves 4 to 8 inches from twig tips showing a slight potassium-deficiency necrosis. In other orchards the trees may exhibit symptoms of severe potassium hunger, but at the same time they may show an abnormal amount of pigmentation in the necrotic leaves and typical phosphorus-deficiency mottling on old leaves.

One symptom that is particularly characteristic of this compound deficiency is an early cessation of terminal growth. This is typical of phosphorus deficiency in peaches. It is not uncommon, however, for growth to be resumed again during the same season.

In plate 13, page 264, peach leaves show typical symptoms of potassium deficiency and at the same time have small, abnormally pigmented dots. The over-all color of the leaves is ochre green, a characteristic of phosphorus deficiency. Moreover, they exhibit a mottling between the veins that is common to phosphorus-deficient leaves but does not occur on leaves lacking only potassium.

Under orchard conditions, peach trees affected by compound phosphorus-potassium deficiency may at times exhibit symptoms of nitrogen deficiency. In fact, such trees usually respond to applications of nitrogen, although relatively large amounts are necessary. This nitrogen deficiency appears to be induced by the lack of potassium. It may be recalled that this was found to occur also when peach trees were deficient in potassium but adequately provided with other nutrients. When this condition develops, immature leaves remain small, and those on the upper halves of current-season twigs become somewhat crinkled, while the margins tend to roll toward the midribs. At the same time, leaves on the lower portion of the twigs may droop and show phosphorus-deficiency mottling. Red pigmentation is particularly abundant and increases in intensity from the bases to the tips of twigs. Fruit buds are very sparse or entirely lacking. Foliage and twig symptoms associated with this compound deficiency are illustrated in plate 14, page 265.

This type of growth has been observed on peach trees, particularly on 1- and 2-year-old trees, in New Jersey for many years. It was recognized as a physiological ailment and was called "false little peach" because the small size, discoloration and drooping of foliage on the lower portions of twigs resemble that caused by the virus disease "little peach." Within recent years, however, work at the New Jersey Agricultural Experiment Station has demonstrated that false little peach is caused by a compound deficiency of phosphorus and potassium.

SMALL FRUITS

The characteristic symptoms of nutrient deficiencies in the various small fruits closely resemble those in other plants insofar as their general pattern and mode of appearance are concerned. It should be borne in mind that by the time a typical deficiency symptom has developed, the plant has slowed down considerably in its growth processes and an economic loss has been suffered by the producer. Every effort should be made to recognize symptoms in their incipient stages, or better still, to prevent their appearance entirely. Soil-analysis or plant-tissue tests may be useful in determining the lack of a nutrient element before the deficiency symptoms occur. Corrective measures can then be applied before plant growth and yield have been reduced.

The importance of detecting the lack of adequate nutrients in the soil, prior to the appearance of deficiency symptoms in the plant, is emphasized in the report of Harris (10). Red raspberry plants growing on a glaciated, light, sandy loam showed significant increase in growth and yield from applications of manganese even though no visible symptoms of manganese deficiency were evident. Applications of boron increased the vitamin C content of the fruit, and zinc increased the total carbohydrate content of the plants. As with the manganese, no visible symptoms of boron or zinc deficiency were evident. It was concluded that in the area under investigation, deficiencies of boron, manganese and zinc may become pronounced enough to warrant their use in fertilizer programs.

Powers and Wood (17) reported a reduction in leaf scorch of raspberries on silt loam soil when potash fertilizers were applied. Zinc, copper and magnesium likewise improved growth and increased yields.

Serious deficiencies of nutrient elements other than nitrogen have not been common in temperate zone plantings of small fruits

in the past. There is an increasing amount of evidence, however, which indicates that deficiencies of a number of elements may become more common in the future. This is especially true on sandy or gravelly soils which are subjected to excessive tillage and leaching.

STRAWBERRIES

Nitrogen Deficiency

The beginning of nitrogen deficiency in strawberry plants is indicated by the yellow-green color of old leaves and by the small size of newly maturing ones. The plants thereafter form relatively few and weak runners. As the deficiency of nitrogen becomes acute, young leaves also acquire a yellow-green color, while mature foliage becomes yellower and at the same time becomes pigmented with red, especially toward the margins of blades. This stage is soon followed by the firing and withering of old leaves near the crowns.

Phosphorus Deficiency

A deficiency of phosphorus in strawberry plants is indicated first by abnormally dark-green foliage resulting from the accumulation of purplish pigmentation in the leaf surface. This symptom is followed successively by (1) a reduction in leaf size or an intensification of the dark color, which changes to coppery purple, and (2) a mottling and dying of old leaves.

Potassium Deficiency

Strawberry plants exhibit definite symptoms of potassium deficiency by the development of marginal leaf scorch. This scorching may be distinguished from the firing, or marginal necrosis, caused by nitrogen deficiency in that the latter is produced first on old leaves and is always preceded by pronounced yellowing and reddening. Scorch due to potassium deficiency, on the other hand, usually develops first on mature leaves of intermediate age and may not be confined to margins. Moreover, the scorched leaves may have a fairly normal green color except for the areas of dead tissue, or they may show more or less purple-red pigmentation.

Calcium Deficiency

Unlike those of the nutrients previously discussed, a deficiency of calcium affects the buds or growing points of the crown first. These tissues are killed, and subsequent growth must take place

from lateral buds. Very young leaves, as well as those that are half grown, may also be affected. The entire leaf, or leaflet, or a portion of a leaflet, may die. Red-brown discoloration may develop around the base of the leaflet, or it may be more or less general over the leaf surface.

Roots usually show considerable injury before the tops are seriously affected. The root injury becomes progressively worse as the deficiency continues. Roots die back from their tips after making relatively short growth. This is followed by the development of new rootlets behind the dead portion. The entire root system, therefore, consists of a small mass of short growths.

Magnesium Deficiency

Magnesium-deficient strawberry plants develop abnormally thin leaves, which exhibit a bright green color not found in healthy foliage. Blotching begins near the margins of old leaves and spreads until the whole surface is necrotic. The affected areas usually exhibit a slightly purple, gray-brown color. Withering of the injured leaves progresses from the bases upward toward the young leaves.

GRAPES

Numerous research workers have reported on various nutrient-deficiency symptoms of grapes. These resemble in general those which have been described for strawberries.

Boron Deficiency

Scott and Schrader (19) have published detailed descriptions of boron deficiency symptoms in grapes as well as a critical discussion of the utilization of this element by plants. The early symptoms of boron deficiency are observed as (1) a diffuse yellowing or chlorosis of the younger leaves; (2) brownish, water-soaked areas developing in the apical tendrils; and (3) cupping of the third or fourth leaf from the shoot tip. The exact order of appearance of these symptoms varies with the variety.

The apical internodes of boron-deficient vines are shorter than those of normal vines. All affected parts exhibit abnormal rigidity and brittleness, while young leaves appearing after the onset of the deficiency are often misshapen and malformed. Deficiency symptoms do not develop on the lower leaves of the vine, even though the terminal parts are extremely affected. On rapidly growing

shoots of the grape, the fifth or sixth leaf from the tip is the oldest one to develop boron deficiency. Apparently the visible symptoms are developed only in those parts where new tissues are forming at the time of occurrence of the deficiency.

The basal leaves of a boron-deficient grapevine may appear normal and yet be just as low or lower in boron than the upper leaves which may show extreme symptoms. Likewise, leaves with extreme boron deficiency symptoms may have a boron content equal to that of normal leaves if samples are analyzed following a period of exposure to an adequate supply of boron. Such apparently contradictory results are logical if it is assumed that only on those leaves which are continuing active cellular development can the symptoms of boron deficiency occur.

Potassium Deficiency

An early symptom of potassium deficiency is interveinal and marginal chlorosis of leaves located at about the middle of the developing cane. As the deficiency becomes more pronounced small necrotic spots develop throughout the older leaves, followed by marginal scorch and yellowing. Young leaves show interveinal chlorosis and marginal scorch.

Magnesium Deficiency

Leaves of grapes receiving an inadequate supply of magnesium develop a water-soaked appearance in the top half of the cane. This is followed by rather large necrotic spots and puckering of the leaves. Leaves of the middle portion of the vine drop off, leaving the center of the cane bare.

PLANT-TISSUE TESTS FOR THE DETECTION OF NUTRIENT DEFICIENCIES

For those who are not familiar with nutrient-deficiency symptoms in fruit trees, plant-tissue tests for major nutrients usually offer a simple and reliable method for confirming a diagnosis. Also, where the identification of a deficiency is complicated by the presence of insect, disease or spray injury, these tests may prove very useful. Moreover, in very light or in acid soils, growth may be inhibited to such an extent that positive symptoms of a nutrient deficiency may be lacking. For several years the senior author has prepared extracts from apple and peach twigs as a means of comparing the composition of the plants with the growth characteristics.

Extracts are prepared in the following manner: Several twigs that are well exposed and representative of nearly the best growth on a tree are selected. A low content of nutrients in weak side branches or in insect- or spray-injured

twigs is not in general an indication that a deficiency is limiting the growth of the tree. Five-gram samples of finely minced tissue comprising the terminal 5-inch portions of apple twigs or 6-inch portions of peach twigs are prepared. These are placed in small mortars to which are added ¼ gram of Darco brand, phosphorus-free, powdered charcoal, and 25 milliliters of the Hester soil-extracting solution (11). The latter contains 5 grams of sodium hydroxide and 10 milliliters of glacial acetic acid, made to a volume of 1 liter with distilled water. In order to facilitate grinding, only about 10 milliliters of the extracting solution are added at first. The tissue is ground for about 5 minutes, and then the remainder of the solution is added and the grinding is continued for another 5 minutes. The extract is filtered through a Whatman No. 1 paper. A clear extract is necessary. If a small amount of charcoal should come through, it may be removed by re-filtering with the same paper. If much yellow or brown color is present, an additional ¼ gram of charcoal should be used. When the color persists, an additional 25-milliliter portion of extracting solution may be used. In general, no extra charcoal or extracting solution is necessary for peach-twig samples. The same is true of apple twigs collected during the spring and early summer. During the late summer and fall, however, most apple twigs contain sufficient tannin to impart yellow or brown discolorations to the extracts. Fortunately, it is often possible by working rapidly to complete estimations of phosphorus and of magnesium content before the color in the extract interferes too much.

Hester (12) proposed the use of a Waring blender for preparing plant-tissue extracts. This machine has four small, stainless-steel blades that rotate at a speed of 10,000 or 12,000 revolutions per minute and quickly reduce the tissue to a pulp. From 10 to 20 grams of tissue, ½ gram of charcoal, and 100 to 200 milliliters of extracting solution are placed in the machine and ground for 5 minutes. The extract thus prepared is filtered as described.

The nutrients may be estimated by the methods described by Hester (11), or Carolus (3), or by other methods that may be suitable. The senior author used for this purpose modifications of quantitative methods used for blood analysis. All values are expressed as parts per million of the nutrient elements in the green tissue.

The nutrient content of extracts from trees making poor growth may be compared with that of extracts from similar varieties of trees making good growth. In general this procedure should be adopted in addition to the use of chemical standards until one has acquired experience with these tests.

Terminal portions of apple and peach twigs have not been found to be greatly different in nutrient content; a deficiency of phosphorus in either case may be suspected when 5- or 6-inch twig tips during the growing season contain less than 50 parts per million of this nutrient. The following table may be useful as a guide in interpreting the results of such tests on apple and peach twigs:

PARTS PER MILLION OF NUTRIENTS IN TERMINAL PORTIONS OF GREEN APPLE AND PEACH TWIGS[1]

Nutrient element	*Deficient Trees* *p.p.m.*	*Good Trees* *p.p.m.*
Phosphorus	Less than 100	200- 700
Potassium	" " 1,000	2,000-7,000
Calcium	" " 100	300-1,000
Magnesium	" " 60	200- 500

Inasmuch as apple and peach twigs do not normally contain more than traces of nitrate nitrogen, if any, testing for it is unnecessary.

Plant-tissue tests are particularly valuable in that they not only reveal a low content of a nutrient but also frequently confirm other evidence. Thus, when calcium or magnesium is deficient in peach twigs, potassium alone or both magnesium and potassium tend to be present in relatively large amounts. Likewise, when only potassium is deficient, calcium or magnesium or both may be found in relatively high concentrations.

[1]Terminal 5 inches of apple twigs or terminal 6 inches of peach twigs.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS IN DECIDUOUS FRUIT TREES

ELEMENT DEFICIENT

A. Symptoms which, in the early stages of the deficiency, are general on the whole tree or tend to be localized in the older leaves of the current season's growth.

B. Symptoms rather generally distributed but usually most prominent on lower leaves of current season's growth. No areas of dead tissue developing on foliage except in advanced and severe cases.

C. Leaves yellowish green; discoloration begins on old, mature leaves and progresses toward the tip. Accumulations of reddish and purplish-red pigments usually obvious. Under prolonged deficiency, twigs hard and slender and foliage small.................................. Nitrogen

C. Young and nearly matured leaves dark green, while mature leaves are bronzed or ochre-dark green. Old leaves usually mottled with light-green areas developing between dark-green veins. Stems and leaf-stalks developing abnormal amounts of purplish pigment, especially during cool summer weather. As the deficiency continues, new twigs slender and leaves small (apple) or strap-shaped (peach)............ Phosphorus

B. Symptoms appearing first on mature or lower portion of current season's growth and occurring as mottling or chlorosis, with or without spots, blotches, marginal scorching or other necrotic (dead) areas in foliage.

C. Foliage necrosis (death of tissues) varying in size from very small spots or dots to patches or extensive marginal areas. Foliage, especially of peach, usually crinkled. Necrotic areas developing first on mature leaves near the middle or lower half of the current season's growth. Twigs usually slender.. Potassium

C. Foliage necrosis occurring as fawn-colored patches on most mature, large leaves. Affected leaves dropping progressively toward the tips of the current season's twigs. Severe defoliation common, leaving a tuft or rosette of thin, dark-green leaves at the terminals................. Magnesium

C. Foliage small, narrow, more or less crinkled, and chlorotic at tips of new growth; twigs slender, with very short internodes near tips, producing rosettes of leaves. Defoliation progressive from bases to tips of twigs. Zinc

A. Symptoms appearing first on young tissues and tending to be localized at the terminals of twigs.

B. Twigs dying back from terminals. Newly developing or nearly mature leaves showing severe necrosis.

C. Immature leaves, especially those at terminals, dying back from tips and margins or along the midribs. Following severe injury to foliage at terminals, twigs dying back for an indefinite distance. These symptoms always associated with injury to root tips................. Calcium

C. Leaves more or less chlorotic and wrinkled; sometimes abnormally thick and brittle. In severe cases, dieback of twigs and spurs. With bearing trees, deficiency associated with necrotic areas in the flesh or on the surface of fruits even when no abnormal growth is apparent in vegetative parts... Boron

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Plate 1.—Nitrogen-deficiency symptoms in apple twig. Note the relatively small, yellowish-green leaves and the reddish leaf stalks, which form narrow angles with the stem.

Plate 2.—Symptoms of phosphorus deficiency in a growing tip of the apple. Leaves are abnormally small and dark green, with conspicuous purple pigmentation. Twig is slender and abnormally purplish.

Plate 3.—Successive stages of marginal scorching due to potassium deficiency in apple foliage. Upper leaf is normal. An early stage is shown by the dark-purplish discoloration of leaf on lower left. Well developed scorch is shown in leaf on lower right. Leaves are typical of those found along mid-portions of current-season twigs. After exposure to rain the scorched areas turn dull brown.

Plate 4.—Symptoms of prolonged and severe potassium deficiency in the apple. In this stage, scorched leaves may be found near the tips of twigs. Dark areas in upper leaf are due to plasmolysis preceding scorching.

Plate 5.—Symptoms of calcium deficiency in young and nearly mature apple leaves. Top row, upper and lower surfaces of young leaf showing early stages of discoloration and death of tissues. Bottom row, upper and lower surfaces of nearly mature leaf showing extensive areas of dead tissue.

Plate 7.—Symptoms of magnesium deficiency in the apple. Three leaves showing successive stages of blotching. This type of necrosis starts near the base of current-season growth and progresses toward the tip. All stages of blotching may occur in leaves on the same twig.

Plate 6.—Symptoms of calcium deficiency in mature apple leaves. Top row, upper and lower leaf surfaces showing a mottled type of discoloration and necrosis (death of tissues). Bottom row, upper and lower surfaces showing a marginal type of necrosis.

Plate 8.—Early, intermediate and advanced stages of nitrogen deficiency in peaches as revealed by leaf symptoms (left to right).

Plate 9.—Successive stages of magnesium deficiency in peach foliage. Large leaves are from Elberta trees grown in sand culture in a greenhouse. Small leaves are from seedling trees grown in the field.

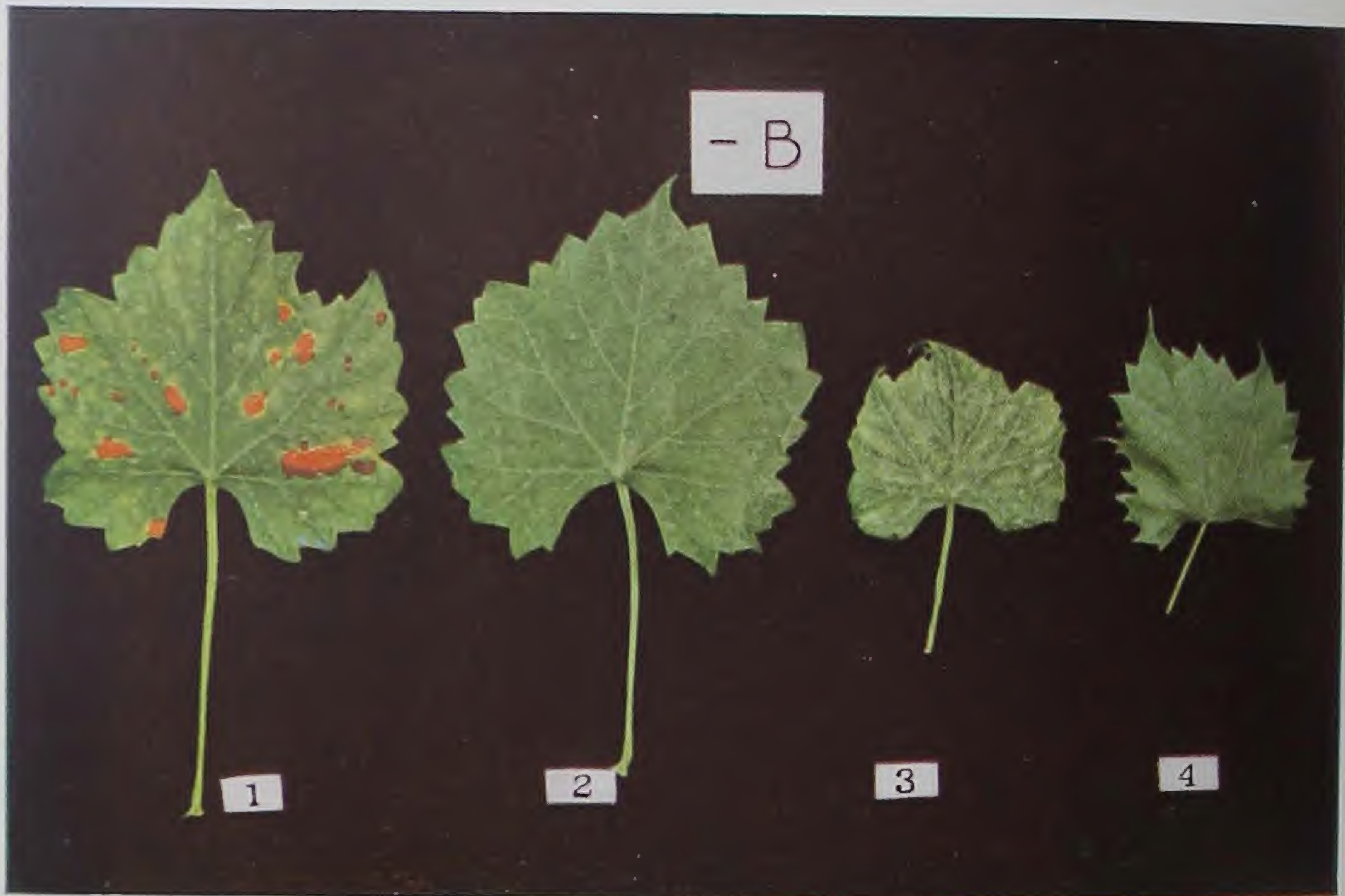
Plate 10.—Symptoms of phosphorus deficiency in the peach. A, an early stage in which leaves, especially those on the lower half of current-season growth, are pigmented with a slight amount of purple and considerable bronze. B, terminal twig showing mottling and curving of blades. C, leaf discoloration characteristic of advanced phosphorus deficiency preceding dropping of leaves.

Plate 11.—Symptoms of potassium deficiency in the peach. A and B, severe potassium deficiency in new spring growth. C and D, crinkling and curling of leaves—an early symptom of the deficiency. E, necrotic spots on small basal leaf from side branch. F, necrotic spotting and marginal scorching following stage D.

Plate 12.—Symptoms of calcium deficiency in the peach. A, an early stage of the deficiency in a growing tip. B, an advanced stage of calcium deficiency in peach twig and foliage. C, midrib necrosis in mature leaf. D, discoloration and necrosis of blade of basal leaf from young side branch of current-season branch. E, necrosis of blade tissue of nearly mature leaf.

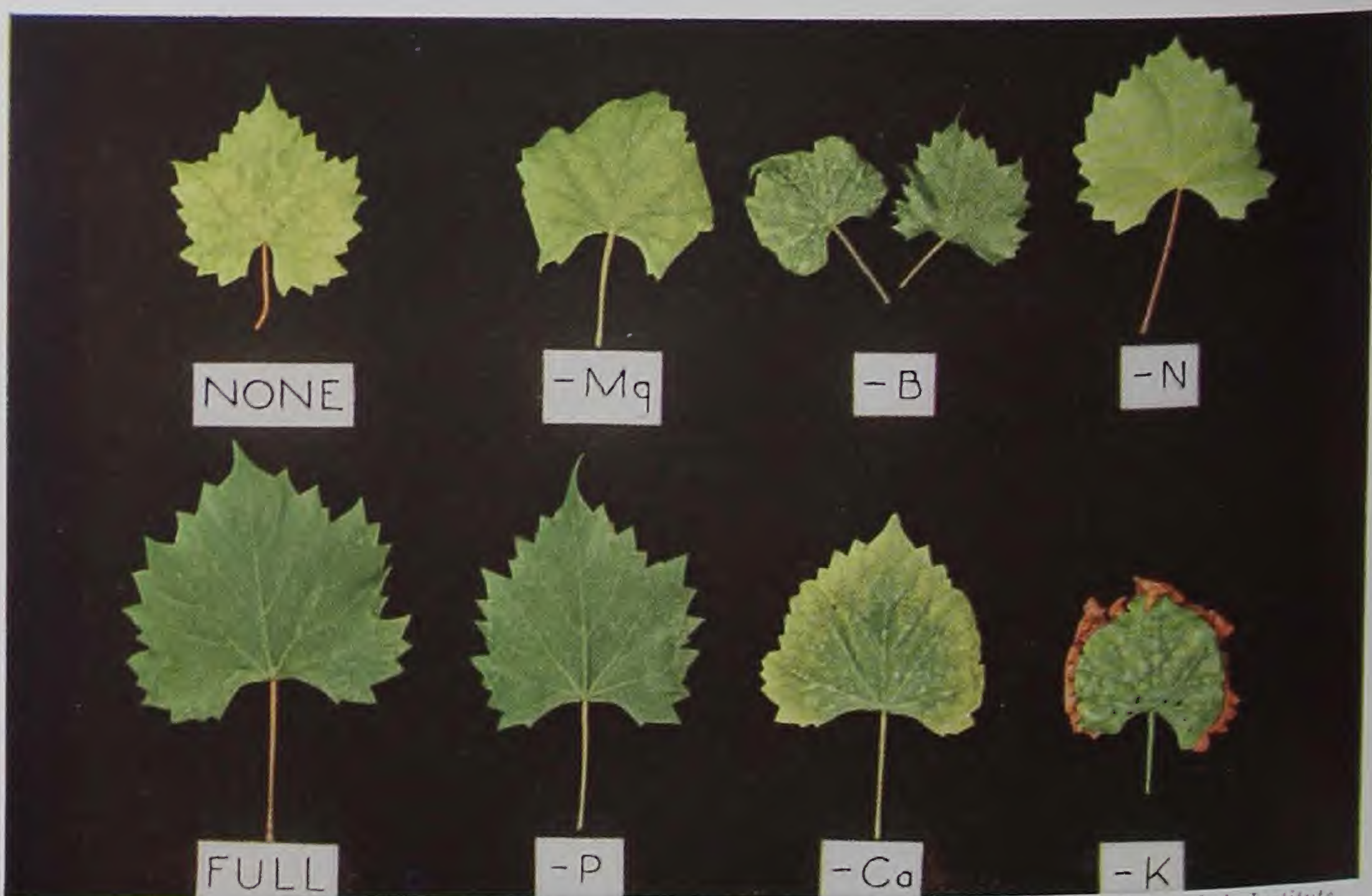
Plate 13.—Foliage symptoms of compound phosphorus-potassium deficiency in the peach. Mottling and color resemble symptoms of phosphorus deficiency. Curling, spotting and necrosis are caused by potassium deficiency. The symptoms of potassium deficiency appear to be superimposed upon those of phosphorus deficiency.

Plate 14.—Symptoms of compound phosphorus-potassium deficiency ("false little peach") in a twig from a field-grown nursery peach tree. Notice similarity in characteristics of basal leaves on this twig and those shown in plate 10-B. Leaf scorch is due to potassium deficiency.



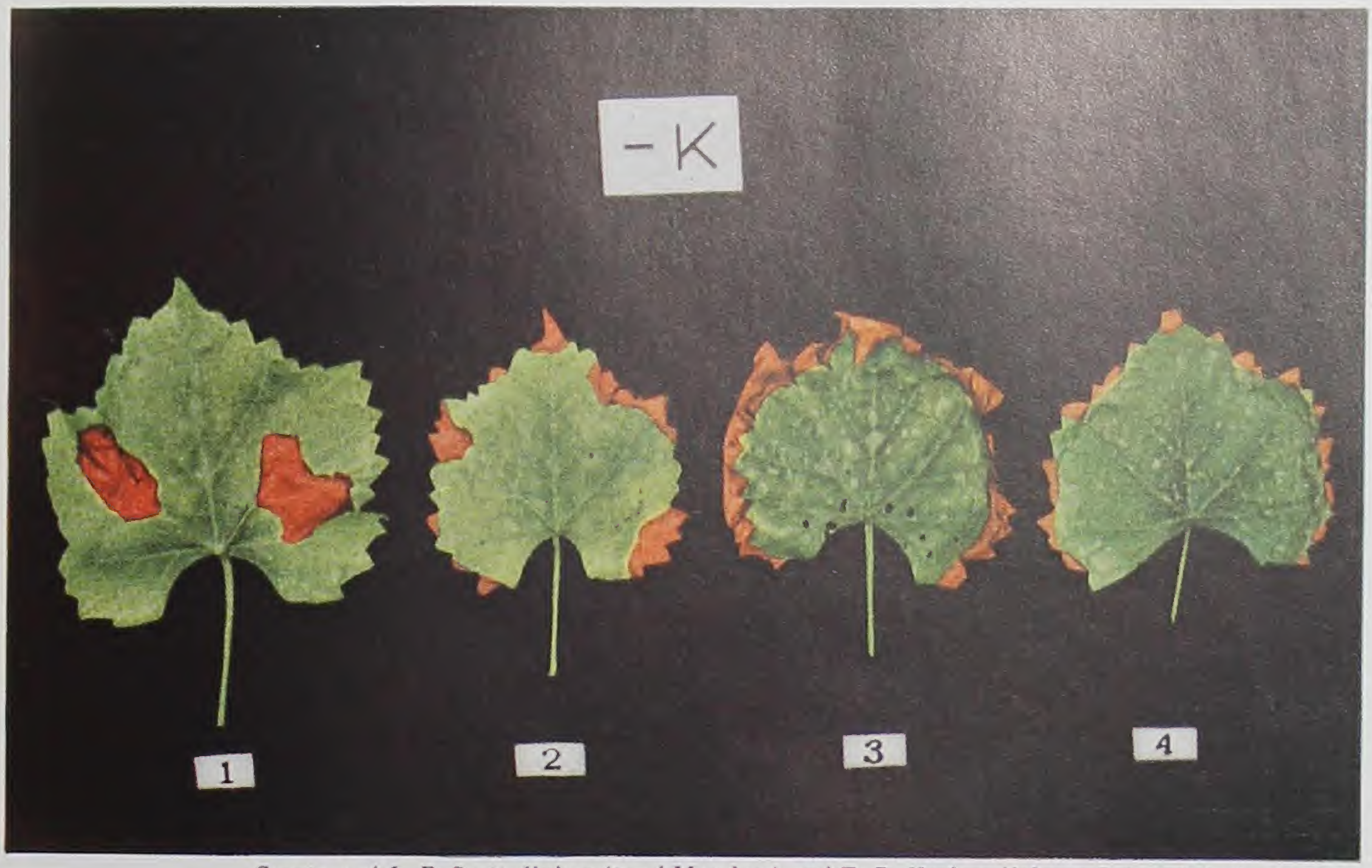
Courtesy of L. E. Scott, University of Maryland, and T. B. Hagler, Alabama Polytechnic Institute

Plate 15.—Boron-deficiency symptoms on leaves of the Hunt muscadine grape when grown in sand culture. Leaf numbers indicate maturity of leaves: 1, mature, 4, immature.



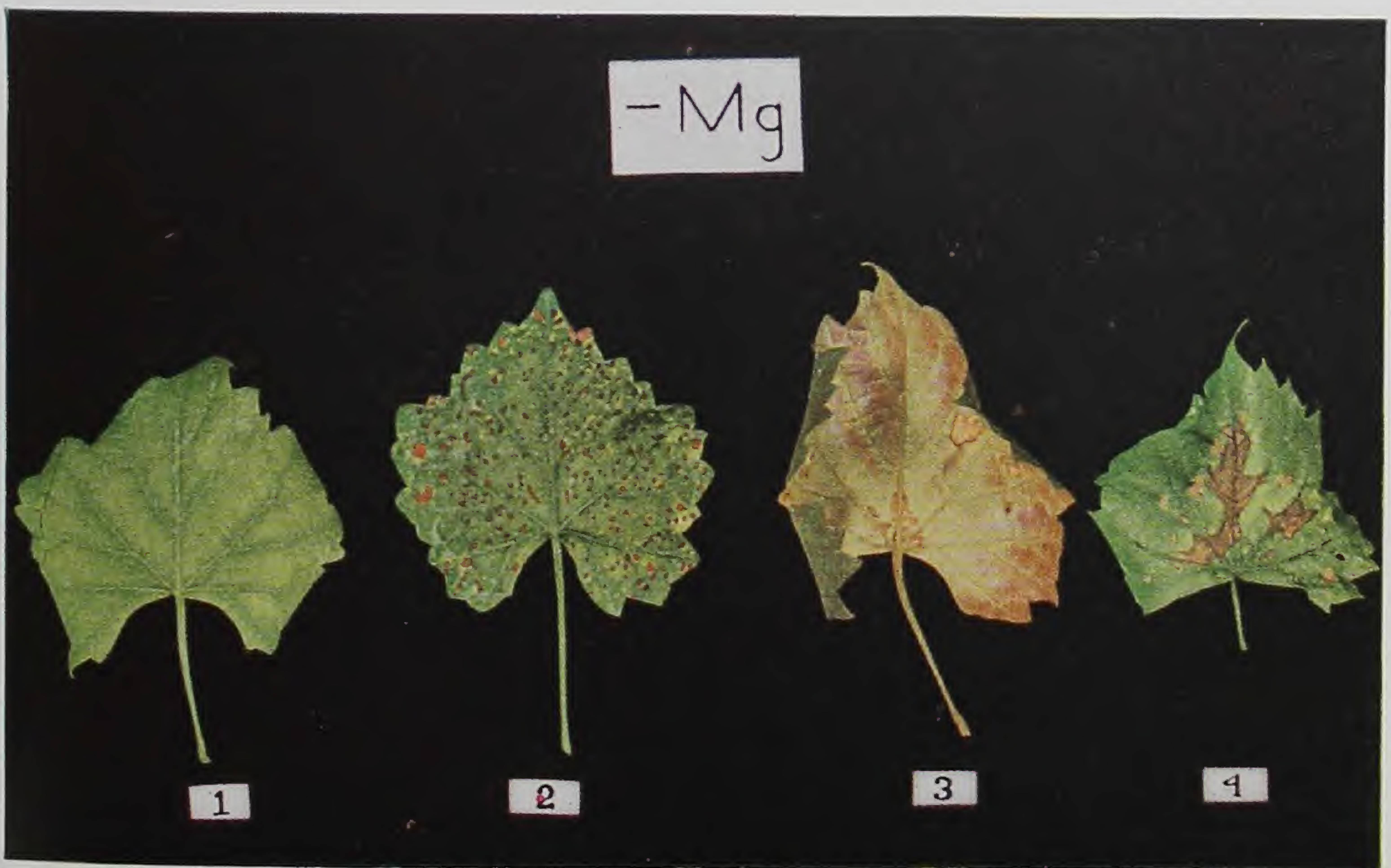
Courtesy of L. E. Scott, University of Maryland, and T. B. Hagler, Alabama Polytechnic Institute

Plate 16.—Leaves of the Hunt muscadine grape when grown in sand culture supplied with nutrient solutions lacking the elements as indicated in the picture.



Courtesy of L. E. Scott, University of Maryland, and T. B. Hagler, Alabama Polytechnic Institute

Plate 17.—Potassium-deficiency symptoms on leaves of the Hunt muscadine grape when grown in sand culture. Leaf numbers indicate maturity of leaves: 1, mature, 4, immature.



Courtesy of L. E. Scott, University of Maryland, and T. B. Hagler, Alabama Polytechnic Institute

Plate 18.—Magnesium-deficiency symptoms on leaves of the Hunt muscadine grape when grown in sand culture. Leaf numbers indicate maturity of leaves: 1, mature, 4, immature.

CHAPTER VIII

Plant-Nutrient Deficiency Symptoms in Legumes

By Werner L. Nelson and Firman E. Bear[1]

PLANT FAMILIES have certain distinguishing characteristics in makeup and in physiology. Legumes are characterized by pods in which the seed are borne. A more important distinguishing characteristic is the presence of nodules on their roots. The bacteria in these nodules fix free gaseous nitrogen, which is incorporated into various compounds in the plant.

Many of the legumes are very good indicators of certain nutrient unbalances, as these unbalances are often revealed by characteristic deficiency symptoms. This is especially true of the broad-leaved legumes. Much experimental work has been done to identify the causes of the chlorotic conditions and plant malformations that appear. Considerable work remains to be done on some aspects of the problem, however, because of the interrelationships among the nutrients and the peculiar effects of environment on the appearance of the symptoms. The amount and distribution of rainfall, as well as of light and temperature, have considerable effect. In addition, varieties differ in their responses to applied fertilizer and in the characteristics of their deficiency symptoms (2).

Certain legumes are relatively exacting in their calcium and soil-reaction requirements. They contain much more calcium than do many of the nonlegumes. This affects the potassium nutrition, in that plants which are high in calcium generally have greater difficulty in securing sufficient potassium from low-potassium soils.

The nutritional status of legumes, as well as of many other plants, may be divided into six general levels as follows:

(a) Deficiency—The plant is stunted and certain of its parts are abnormal in color or shape.

(b) Poverty adjustment—The plant may show no symptoms of deficiency, but the yield is low.

(c) Optimum—The plant has maximum growth. This level exists only in theory, but it may be approached in practice.

[1] Werner L. Nelson is professor of agronomy, North Carolina State College of Agriculture and Engineering, and Firman E. Bear is chairman, soils department, New Jersey Agricultural Station of Rutgers University. Chapter VIII in the first edition was written by E. E. De Turk, Professor of Soil Fertility, University of Illinois.

(d) Luxury Consumption—The plant appears the same as at the optimum level.

(e) Moderate toxicity—The plant is stunted.

(f) Toxicity—The plant is stunted and certain of its parts are abnormal in color or shape.

A large majority of our crops belong in the (b) group with respect to one or more of the essential elements. Legumes, in particular, may live and grow under conditions of moderate deficiency of some nutrients without showing any visual symptoms. Growth may be reduced but, with the whole field in the same condition, the stunting may not be noticed. Lowered production may result for a number of years without realization on the part of the farmer. Eventually, however, the soil is depleted to the point where the plants show deficiency symptoms. Certain of these symptoms are described in the following pages.

CALCIUM DEFICIENCY AND SOIL ACIDITY

One of the earliest soil treatments that produced observable effects on legumes was the application of liming materials to acid soils. This resulted in larger plants with darker green leaves. Over the years, much has been learned about the reasons for these and other beneficial effects from liming the soil.

Calcium, in the form of liming materials, has several effects. First, it is an essential nutrient element. Legume plants are relatively high in calcium and usually have a high calcium requirement. The ease with which the plants can secure this element from the soil is influenced not only by the amount of it in the soil but by the degree of cation saturation of the soil colloids, the kind of colloids, and the nature of the other cations on them (1, 25, 32).

Second, lime makes the soil less acid. This brings about several indirect effects. One of these is related to the activity of the nitrogen-fixing organisms (nodule bacteria) (19). Under acid conditions the bacteria cannot function effectively and the legume may be deficient in nitrogen. Certain elements, such as manganese, aluminum, iron and zinc, may go into solution in toxic quantities under acid conditions. Additions of lime reduce the amounts of these elements in solution, and high application rates may actually reduce the quantities in solution to deficiency levels (43).

The ratios among the amounts of calcium, magnesium and

potassium in soils and plants are important. Bear et al., after studying 20 New Jersey soils, suggested that, for alfalfa, 65 percent of the exchange complex of the soil should be occupied by calcium, 10 percent by magnesium, 5 percent by potassium, and 20 percent by hydrogen (6). Alfalfa tends to take up more potassium than it needs, unless the calcium content of the soil is maintained at a relatively high level.

Courtesy of Department of Agronomy, North Carolina State College

Figure 1.—Lime response of Virginia Bunch peanuts. On this soil, low in calcium, peanuts show a very marked growth response to the application of one ton of limestone. The larger, greener plants are on the limed plots.

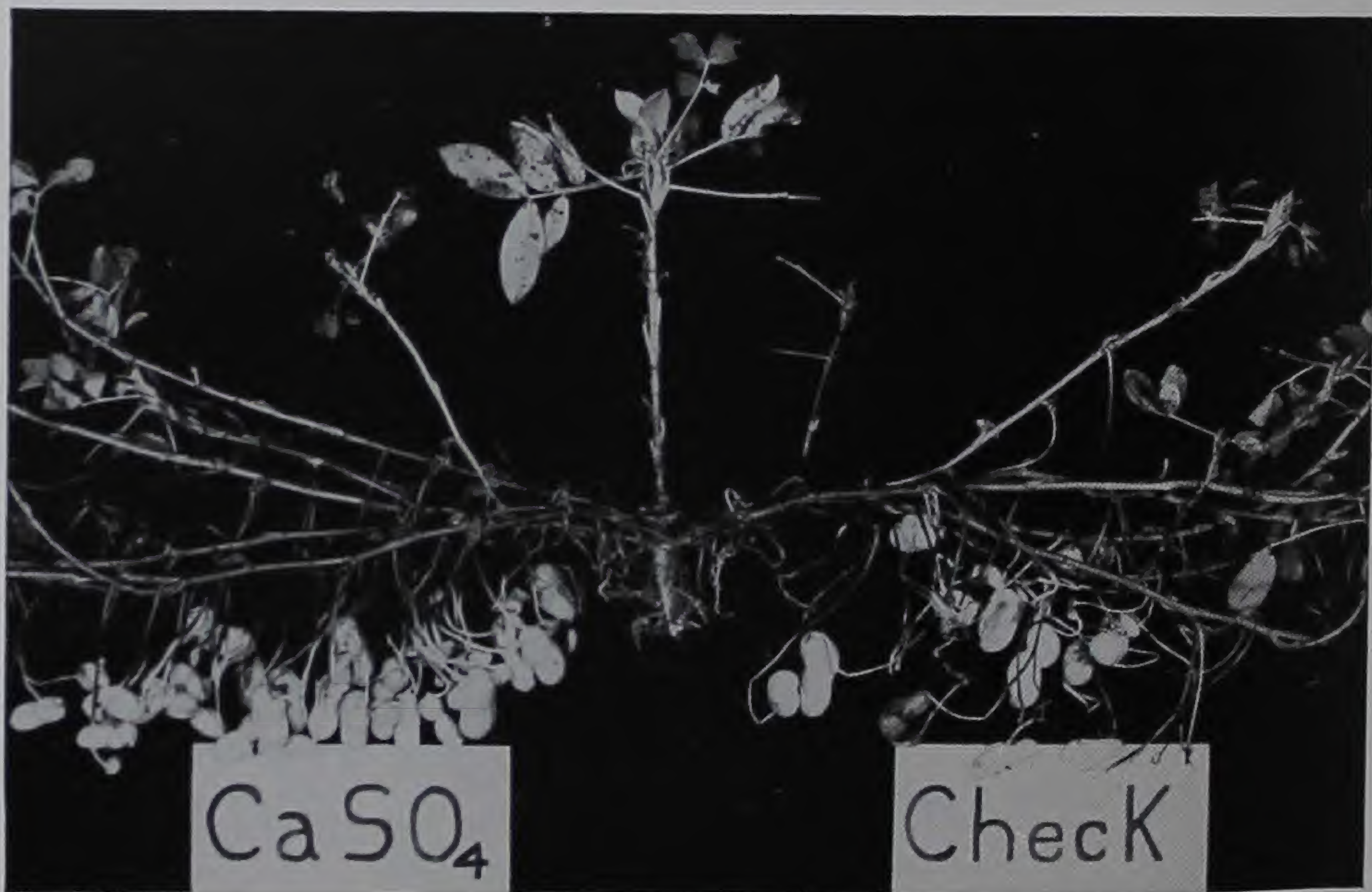
Symptoms

Calcium-deficiency symptoms have frequently been produced on legumes in controlled greenhouse experiments. Distinct symptoms are rarely seen, however, under field conditions. Most of the effects of lime on legumes are indirect, and are related to its influence on nitrogen fixation and on the availability of other plant nutrients, principally the trace elements. These effects will be discussed in detail in the sections on nitrogen deficiency and trace elements.

Some years ago, farmers in the Middle West began to be troubled with loss of stand of the clover that was seeded in small grains. Too, the clover was not knee-high by fall, as it had been formerly. In many cases, this was attributed to "dry weather." The clover that lived was subject to winter killing and heaving the first winter, and it seemed as if both summer and winter weather were becoming

more adverse. The difficulty was found to be related partly to the acidity of the soil. Additions of liming materials usually helped to remedy the situation.

The legumes that are most sensitive to soil acidity and lack of calcium are, for the most part, the small-seeded ones, such as alfalfa, sweet clover and red clover. Such seeds have little reserve, the root systems of the seedlings are limited, and the plants grow very slowly at first. When growth is slow, plants are very apt to succumb to summer drought and winter killing during the first year.



Courtesy of Department of Agronomy, North Carolina State College

Figure 2.—Low calcium in the fruiting zone of large type Virginia peanuts shows at harvest in the form of many pops (unfilled shells). Calcium sulfate (land plaster) was applied in the fruiting zone on one side of the plant but not on the other. Note the well developed nuts obtained by applying calcium sulfate (left).

The effect of lime on peanut growth on a low-calcium soil is shown in figure 1. Applications of lime gave larger, greener plants and greatly increased yields. With large-type Virginia peanuts, a high percentage of pops (unfilled shells) at harvest is a good sign of calcium deficiency. The calcium level in the fruiting zone has a definite influence on the filling of the fruit. A low level of calcium gives many pops (figure 2). The response of Spanish peanuts, or small-runner types, to soluble calcium is not as marked (26).

Red clover, when grown in sand cultures, exhibits pronounced calcium-deficiency symptoms if calcium is omitted from the com-

plete nutrient solution (13). The plants grow normally at first, with only the calcium that is contained in the seeds. The plants soon stop growing, however, and evidence of deficiency appears a few days later. The symptoms are mainly of three kinds: (a) Chlorosis appears in the form of small white dots, distributed irregularly over the entire surface of full-grown older leaves. After 6 to 8 days, these dots become gray, and the rest of the leaf grayish green. (b) Many of the petioles of the older leaves collapse,

Figure 3.—Calcium-deficient red clover. Note the collapsing leaf stalks. The leaf blades remain turgid for some time before wilting occurs.

Courtesy of Department of Agronomy, University of Illinois

allowing the leaf to droop, but without immediate wilting of the leaf blades (figure 3). After several days, these leaves wither and die. (c) The emerging young leaves are small, undeveloped and unfolded, and the petioles do not lengthen. More new leaves emerge similarly, in rapid succession, forming a clump at the crown. Calcium deficiency is generally manifested in the actively

growing parts, as calcium is relatively immobile in the plant.

Though the functions of calcium are not fully understood, the symptoms observed would indicate that this element plays a role in cell-wall formation. Weakening of the cell walls causes the sudden collapse of the leaf petioles. In nitrogen or potassium deficiency, dehydration or drying-out occurs first.

With most crops, the calcium problem is taken care of by an intelligent liming program. With peanuts, however, a relatively soluble source of the element, such as calcium sulfate, may be required, in addition to or in place of lime, in order to insure a high calcium level in the fruiting zone (36).

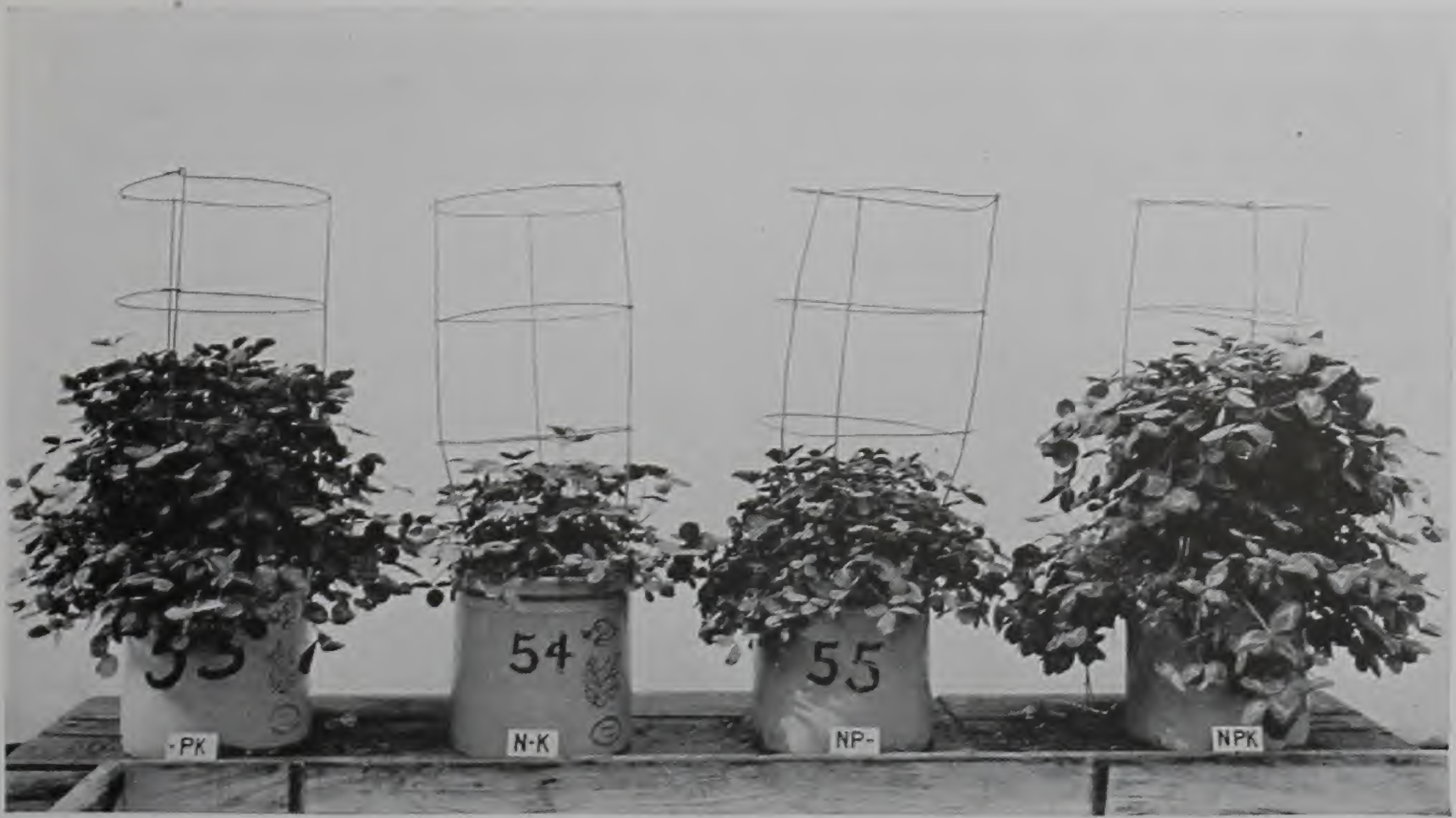
NITROGEN DEFICIENCY

If legumes are to be supplied with adequate quantities of nitrogen, it is first necessary that a sufficient number of the proper nodule bacteria be present to carry on nitrogen fixation. There are several different groups of nodule bacteria and each group inoculates a given legume or group of legumes. For example, the nodule bacteria that inoculate alfalfa will not function on soybeans. Good inoculation is shown by large nodules centrally located on the root system. When a new legume is introduced into an area, artificial inoculation is commonly necessary the first year or two that it is planted.

The effect of inoculation on soybeans is shown in plate 1, page 297. This photograph was taken some years ago on the University of Illinois farm. Few such demonstrations are now possible in the Corn Belt because widespread planting of soybeans has brought about extensive distribution of the soybean nodule bacteria in the soil. A similar build-up of alfalfa and sweet clover nodule bacteria has taken place. Nevertheless, it is usually advisable to inoculate the seed before they are grown.

Another example of the need for proper nodule bacteria is shown by an experiment with white clover (plate 2, page 297). Very good growth was obtained by using an efficient strain of bacteria, whereas little growth was obtained with an inefficient strain.

The nitrogen-fixing bacteria must have proper conditions under which to work, once they are in the soil. They thrive only within certain ranges of soil reaction and, in general, their vigor and effectiveness are lowered with increasing soil acidity. The nodule bacteria differ greatly, however, in reaction requirements. For example, red clover bacteria can function efficiently under more acid



Courtesy of Department of Agronomy, Purdue University

Figure 4.—Red clover makes slow growth on an infertile soil when phosphorus or potassium is omitted, second and third pots from left, respectively.

Courtesy of Department of Agronomy, Purdue University

Figure 5.—Sweet clover makes slow growth on an infertile soil when phosphorus or potassium is omitted, second and third pots from left, respectively. This is the same soil as was used for red clover in figure 4. Note the difference in the nitrogen response of the two crops. The soil was apparently too acid for the best functioning of the nitrogen-fixing bacteria on sweet clover.

conditions than can those of sweet clover (compare figures 4 and 5). The length of time the bacteria persist in the soil in the absence of the legume host also tends to decrease with increase in soil acidity. Liming is an essential practice in the maintenance of optimum soil conditions for legume bacteria.

The possibilities in the addition of nitrogen fertilizer to legumes have been investigated. An application of nitrogen at planting is recommended for small-seeded legumes, such as alfalfa, on light soils. The young seedlings may need nitrogen before the nodule bacteria can begin to function.

Norman (31), working on Iowa soils, found that soybeans responded to applications of nitrogen. Although the soybean plants grew well when nodulated, maximum yields were not obtained unless additional nitrogen was supplied. Investigations on three Coastal Plain soils in North Carolina, however, showed little response to nitrogen applications (45). The soils were limed and fertilized and the soybeans were well nodulated. The growing season is longer in North Carolina than in Iowa, and this may allow the nodule bacteria sufficient time to fix adequate quantities of nitrogen.

Another important point that must be considered in the use of nitrogen fertilizers is that they tend to stimulate grasses and weeds and these plants may compete seriously with the legume for the essential mineral elements. Reductions in legume stands may also result.

Symptoms

It is common knowledge that nitrogen-deficient plants are paler green than healthy plants. This is very common in legumes. Deficiency is indicated when the leaves become pale green, with a yellowish tinge. Later the leaves may become distinctly yellow, the chlorosis spreading evenly over their entire surfaces. The deficiency usually appears first on the leaves at the base of the plant, but it spreads quickly to the upper part. Progressive stages of nitrogen deficiency on soybeans are shown in plate 3, page 298. The plants were grown in gravel culture.

Nitrogen-starved leaves remain chlorotic for many days, the plant making no apparent growth. If not allowed to go too long, the green color can be promptly restored by supplying available nitrogen in fertilizer form. Eventually, nitrogen-deficient plants lose their leaves, those on the lower part of the plant dropping first. Analyses have shown these shed leaves to be very low in nitrogen.

If legumes have uniformly pale green to yellow leaves, it is well to dig up some plants to see if the roots are well nodulated. A soil sample should also be taken to determine the pH and calcium levels. On acid soils, liming, adequate fertilization, and artificial inoculation will go a long way toward stimulating the nodule bacteria to fix adequate amounts of nitrogen.

PHOSPHORUS DEFICIENCY

Legumes, as a group, have relatively high phosphorus requirements. Although the amount of phosphorus in legume plants varies widely, it is never as high as that of nitrogen or potassium. On the average, legume hays contain about 2.5 percent nitrogen, 0.5 percent phosphoric acid, and 2.0 percent potash. The seed accumulate relatively large amounts of phosphorus, particularly in the case of the large-seeded legumes.

Symptoms

Symptoms of phosphorus deficiency are not as well defined as those of many other deficiencies. The chief symptoms are a retarded rate of growth and spindly plants, with the leaves turning dark green or bluish green. The response to phosphorus is often most marked during the early growth period. At that time the plants have a limited root system and depend to a large extent on localized applications of the element. Later in the growing season, the response to phosphorus may be much less noticeable. As the roots extend, the plants depend more and more on the soil phosphorus. The growth response of soybeans at blooming time is shown in plate 4, page 298. Plants suffering from phosphorus deficiency tend to be delayed in blooming and maturing.

In certain of the legumes, phosphorus deficiency results in the leaf blades being tilted upward and the leaves may appear to be rather pointed. The stems may also turn red under severe deficiency. This color tends to develop if a lack of phosphorus, or of any other element, interferes with the utilization and transfer of carbohydrates. The accumulated sugars favor the formation of the reddish pigment, anthocyanin. A limited supply of phosphorus also interferes with nodule activity in that the number of nodules, as well as their efficiency of nitrogen fixation, is greatly reduced.

Dwarfed red clover and sweet clover plants grown without phosphorus are shown in figures 4 and 5 (second pot from the left in each photograph). This soil was very low in available phosphorus.

It is usually very difficult to be sure in any given field that the crop is or is not phosphorus-deficient. In fact, the dark green leaves of phosphorus-deficient plants often give the impression that the plants are very healthy. Soil and tissue tests are an aid in determining the level of phosphorus in soil and plant. Phosphate fertilization of a small area in a given field, followed by close observation of growth response, is also desirable.

POTASSIUM DEFICIENCY

Potassium deficiency is perhaps the most outstanding and easily recognized symptom in legumes (17). Most of the common legume species require relatively large amounts of this element. Farmers often fail to consider this fact, and the continued growing of legumes on a given area, without adequate renewal of the potassium, soon depletes the soil of this element. Yields then decrease and deficiency symptoms appear.

Legumes, as a group, require liberal liming. In general, liming increases the potassium requirements on soils having low reserves of this element. Much of this may be attributed to the greater removal of potassium because of the better crops grown after the soil has been limed. In addition, the calcium:potassium ratio in plants is greatly affected by liming. Work on alfalfa indicates that, when this ratio becomes greater than 4:1[2] yields will be depressed, and the plants will respond to potassium applications (6, 22). Potassium-deficiency symptoms will not appear, however, until the ratio becomes approximately 8:1. In other words, high amounts of calcium in relation to potassium disturb the nutrient balance in the plant.

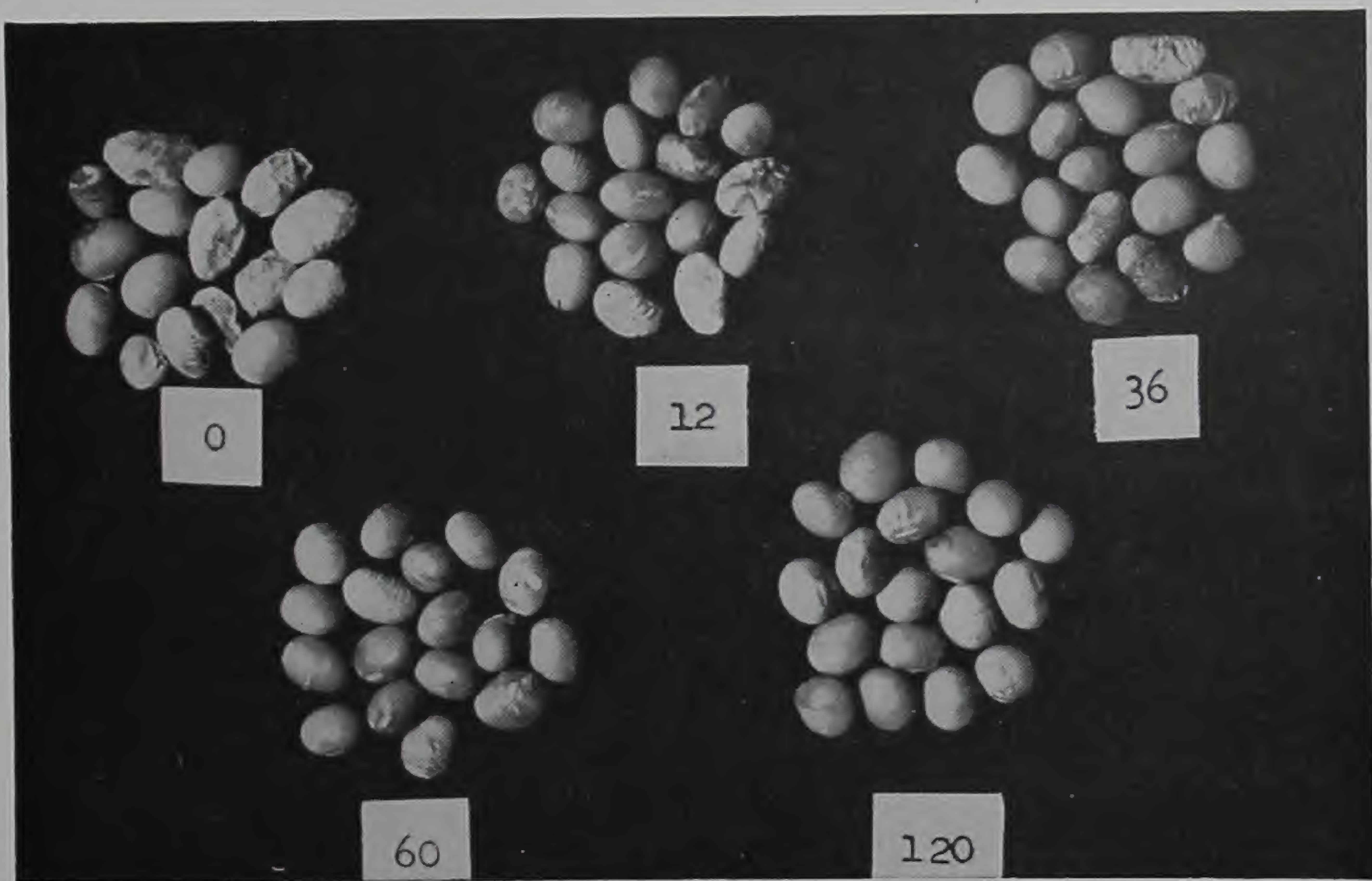
Symptoms

The broad-leaved legumes, such as soybeans, quickly show evidence of insufficient potassium by irregular yellow mottling around the edges of the leaflets (plate 5, page 299). These chlorotic areas soon merge, forming a continuous yellow border around the tip and along the sides of the leaves, but rarely around the base. Death of the chlorotic areas follows promptly, along with a downward cupping of the leaf edges. Then the dead tissue falls out, giving the leaflet a ragged appearance. The marginal firing often spreads to include half or more of the leaflet area, while the center and base still remain green (plate 6, page 299). Potassium-starvation symptoms in cowpeas closely resemble those in soybeans.

[2] Cation-equivalent ratio.

When the supply of potassium gives out late in the growing period, during late bloom for example, pronounced chlorotic conditions are less likely to appear. Instead, the upper leaf petiole below the leaflets turns brown and then black. The leaflets then droop and die. A deficiency of potassium tends to produce poor quality soybean seed (figure 6).

Potassium deficiency is one of the common causes of "alfalfa yellows." This condition may be caused by a variety of other



Courtesy of Department of Agronomy, North Carolina State College

Figure 6.—Seeds of potassium-deficient soybean plants are wrinkled and misshapen. The figures indicate the pounds of potash applied on the growing plants. Note the inferior beans with the low rates of potash.

nutritional factors, however, including deficiencies of boron, nitrogen, manganese and sulfur. It may also be the result of insect injury, so that close examination is necessary in order to identify the specific trouble (11, 12).

Potassium deficiency in alfalfa has been described as follows (11): Small white spots around the margin first appear on the green leaves. Later the tissue between these spots becomes yellowish-green to yellow and finally dies and turns brown (plate 7, page 300). The severity of marginal yellowing increases progressively from the top of the shoot downward to the older lower leaves. In instances of severe deficiency, the symptoms of marginal yellowing may be much

more pronounced than the spotting. Potassium moves very readily within the plant. Under conditions of deficiency, the potassium moves from the lower leaves toward the top of the plant. This helps to explain the more pronounced symptoms on the lower leaves. Care must be used in differentiating between the white spots that are due to insect injury and those resulting from potassium deficiency.

In a crop such as alfalfa, where several cuttings are removed, the intensity of potassium deficiency may increase as the season advances. Often the first cutting may show little of it, whereas later cuttings may show quite severe deficiency. This is explained, in part, by the fact that in winter the potassium-bearing minerals weather to release potassium that is utilized in spring and summer growth. Deficiency symptoms involving only yellow leaf margins, without the spotting, may occur during the middle of the summer.

Stands of alfalfa have been known to persist many years longer when potassium fertilizers were applied. Loss of stands has sometimes been attributed to winter killing. The plants may even die out in the summer. In many such cases the poor vigor of plants, resulting from a deficiency of potassium, has made them more susceptible to injury. Hence, weeds in an alfalfa field may be a hunger sign. In New Jersey, weeds growing in a potassium-deficient alfalfa field contained several times as high percentages of potassium as the alfalfa and, apparently, were growing normally.

A 3-ton crop of alfalfa removes about 135 pounds of potash, the equivalent of 270 pounds of 50 percent muriate of potash. The average grower does not appreciate the extent of this removal. When alfalfa contains less than 1 to 1.25 percent potash, a profitable response from potassium applications may be obtained (6, 9). On the other hand, alfalfa is a good example of a crop that will absorb potassium in considerable excess of the amount needed, sometimes containing as high as 4.0 percent potash. This is called luxury consumption.

Potassium deficiency in Ladino clover is first shown by the appearance of a few small yellow spots, usually near the margins of the leaflets (plate 8, page 300). Necrotic areas soon cover most of the leaf surface, except around the midrib. The edges turn yellow and the leaflets shrivel to an irregular curled shape. The symptoms in alsike (plate 9, page 301), red clover and sweet clover are very much like those in alfalfa and Ladino. The growth responses of red clover and sweet clover are shown in figures 4 and 5.

Peanuts remove large amounts of potassium, but actual deficiency symptoms seldom appear on this crop in the field. Crops such as soybeans, when grown in rotation with peanuts, may suffer severe deficiency, however, if sufficient potassium is not applied. This is a good illustration of the difference in the ability of crops to absorb available potassium. This difference may be related, in part, to the type of root system, but the complete mechanism is unknown.

In general, legumes are stunted in growth before visual potassium-deficiency symptoms become evident. Investigations with soybeans, on Coastal Plain soils, have shown that yield increases from applications of potassium may be expected, even when the leaves do not show marginal yellowing (30). Greenhouse investigations with alfalfa reveal that a yield response to potassium will be obtained, even though deficiency is not extreme enough to cause visual symptoms (6). Field studies in New York, however, under a wide range of conditions, indicate that when less than 15 percent of the plants show deficiency symptoms the yield responses to potassium applications are often not significant (9).

MAGNESIUM DEFICIENCY

Legumes normally contain two to three times as much magnesium as do the grasses (48). Magnesium has an important role in chlorophyll formation in that it is a part of the chlorophyll molecule. Magnesium also plays a role in oil formation. The latter function is particularly important in the large-seeded legumes, which are grown largely for oil.

There is some evidence that magnesium affects the utilization of available soil phosphorus (42). Truog, in working with pea seed, found that the phosphorus content of the seed was increased much more with the use of extra magnesium than with extra phosphorus. This suggests that these two elements are closely related in the nutrition of plants. There is actually a greater amount of magnesium than phosphorus in most legumes.

An abundant supply of potassium tends to decrease the uptake of magnesium. Studies in New Jersey showed that, as the potassium supply decreased with repeated harvests of a crop like alfalfa, the magnesium content of the plant increased, even when it was growing on a soil that was very deficient in this element (34). This indicates the importance of a good supply of magnesium when high amounts of potassium are used.

Magnesium is also related to the nitrogen status of legumes.

Work at Missouri has shown that the magnesium supply definitely affects nitrogen fixation (20). The addition of magnesium under conditions of deficiency made it possible for the nodule bacteria to act more efficiently, and greener, larger soybean plants were produced.

The soils in the Atlantic and Gulf Coastal Plains are most likely to be deficient in magnesium. This is due to the low amounts present and to the depressive effects on magnesium absorption of the liberal amounts of potassium that are being used on these soils.

Courtesy of Department of Agronomy, Alabama Polytechnic Institute

Figure 7.—Mild magnesium deficiency in crotalaria or other legumes may result in only a moderate reduction in growth. Left, low magnesium; right, adequate magnesium.

Symptoms

Magnesium hunger signs vary with the legume and with its stage of growth. In the early stages, the areas between the main veins of the leaves of soybeans and cowpeas become pale green (plate 10, page 301). These areas later turn a deep yellow, except at the base of the leaf. The lower leaves are likely to be affected first.

Appearing at a late stage of growth, magnesium deficiency gives the general appearance of early maturity. There is a curling downward of the leaf margins, a gradual yellowing from the margin inward, and a bronzing over the entire leaf surface. On a magnesium-deficient soil, additions of magnesium were found to retard maturity of soybeans, as measured by their moisture content at harvest time (29).

In crotalaria, magnesium deficiency is shown by a yellowing of a broad margin of the leaf (plate 11, page 302). The base and center of the leaves and, to some extent, the veins remain green. The amount of reduction in growth depends, of course, on the severity of the deficiency. With less intense deficiency, the reduction in growth is not great (Figure 7). In severe cases, however, there is an almost complete yellowing of all leaves, with a marked reduction in growth.

When peanut plants were grown with inadequate magnesium in sand cultures, the older leaves became chlorotic at the leaf margins

(8). This chlorosis later advanced toward the midrib, and the leaf margins became orange in color. With very low magnesium in the rooting and fruiting zone, additions of magnesium increased the number of filled nuts (38). In another type of study, in which the fruiting and rooting zones were separated, the addition of magnesium salts to the fruiting zone was only slightly beneficial to fruit filling (7). In contrast to calcium, magnesium moves rather freely within the plant.

The occasional use of dolomitic lime, when lime is needed, takes care of the magnesium problem with most legumes. Where legumes are grown in rotation with crops requiring an acid soil, such as Irish potatoes, a soluble form of magnesium may be necessary for both crops.

SULFUR DEFICIENCY

Although soils differ considerably in their content of sulfur, most of them contain an adequate supply for legumes. The native supply of this element in the soil is being continuously replenished by that coming down in the rain and snow. The amount of sulfur brought down in this manner may reach 100 pounds per acre per year near urban areas. The sulfur gases in the air are chiefly a result of the burning of coal or other fuels. In sparsely populated areas, the amount brought down in the precipitation may be only 4 to 5 pounds per acre per year. Since sulfur, as sulfate, is continually being lost in the drainage water, certain soils in these sparsely populated areas have become deficient in this element (14).

In regions where legumes are fertilized with superphosphate, or with fertilizers containing it, there is little danger of sulfur deficiency. Superphosphate contains approximately 50 percent calcium sulfate, by weight, and hence furnishes a good supply of sulfur. Some fertilizers also contain potassium sulfate.

Striking responses of alfalfa to applications of sulfur have been obtained in the Pacific Northwest. Responses have also been reported on alfalfa, as well as on other legumes, in certain areas in Minnesota, Montana and North Dakota.

Symptoms

In sulfur-deficient legumes the younger leaves, including the veins, turn pale green to yellow (14, 16). In later stages the older leaves turn yellow. The symptoms are very much like those of nitrogen deficiency, although, when nitrogen is limiting, the older leaves tend to be affected first.

Sulfur-deficient plants usually have a low protein content. This might be explained, in part, by the fact that sulfur is an important part of the protein molecule and any deficiency of the element slows down its synthesis. Poor nodule development and a low rate of nitrogen fixation are also usually associated with sulfur deficiency.

DEFICIENCIES OF TRACE ELEMENTS

A number of the elements that are essential for plant growth are required in such extremely small amounts that these elements are sometimes called trace or minor elements. From the standpoint of the nutrition of growing plants, however, they are just as important as the elements that are used in larger quantities. The trace elements considered in this chapter are boron, manganese, iron, copper, zinc and molybdenum.

One important aspect of the utilization of trace elements is the relation of soil pH values to their availability. Applications of lime to decrease the soil acidity tend to result in a decrease in the availability of certain of these elements. On many soils, the use of relatively large amounts of lime brings about a chlorotic condition in legumes. This is spoken of as "overliming injury," and may be caused by a deficiency of one or more of the trace elements. Since legumes require a reasonably high lime level in the soil, the high incidence of overliming is understandable.

Another important characteristic of trace-element nutrition is that the optimum range in concentration is usually quite narrow. Relatively small increases above the optimum may have toxic effects. This is particularly true with boron. Five to 10 pounds of borax per acre, applied beside the row for soybeans or peanuts, will usually produce toxicity symptoms. On alfalfa, where the borax is broadcast and worked in, however, 40 to 50 pounds per acre may be used without injury.

BORON DEFICIENCY

Boron deficiency has been observed on a number of legume species. The first specific evidence on the importance of boron for plants was shown in 1923 (44). Since that time this element has received much attention. The actual amount of boron needed by plants is very small. A ton of alfalfa will contain about 1 ounce of it. Some soils are so low in boron, however, that they cannot supply even this small amount.

Boron uptake is related to the supply of certain other elements, especially of the cations, and plants make normal growth only when

a suitable balance obtains between the uptake of boron and these other elements. Boron deficiency may be intensified by high applications of potassium (37). Soils that have been liberally limed may also need additional boron, especially if the original supply of this element was low (23). This is the result both of the influence of lime on boron availability and of the increased growth following the use of lime. The high boron requirements of certain legumes thus may be related to the relatively large amounts of both calcium and potassium that are needed by them.

Until a few years ago, it was practically impossible to establish and maintain a stand of alfalfa on many soils, notably on those in Southeastern United States. Applications of boron helped to solve the problem (46). The setting of seed in certain legumes also has been materially increased by boron applications in many areas.

Symptoms

Boron-deficiency symptoms in alfalfa have received the most attention and may be described as follows: The leaves near a growing point are yellowed, sometimes reddened, but all the lower leaves remain a healthy green color (plate 12, page 302). Lateral terminals are sometimes affected. The plants are stunted by a shortening of the terminal internodes, resulting in rosetting, flowers fail to form, and buds appear as white or light brown dead tissue (12).

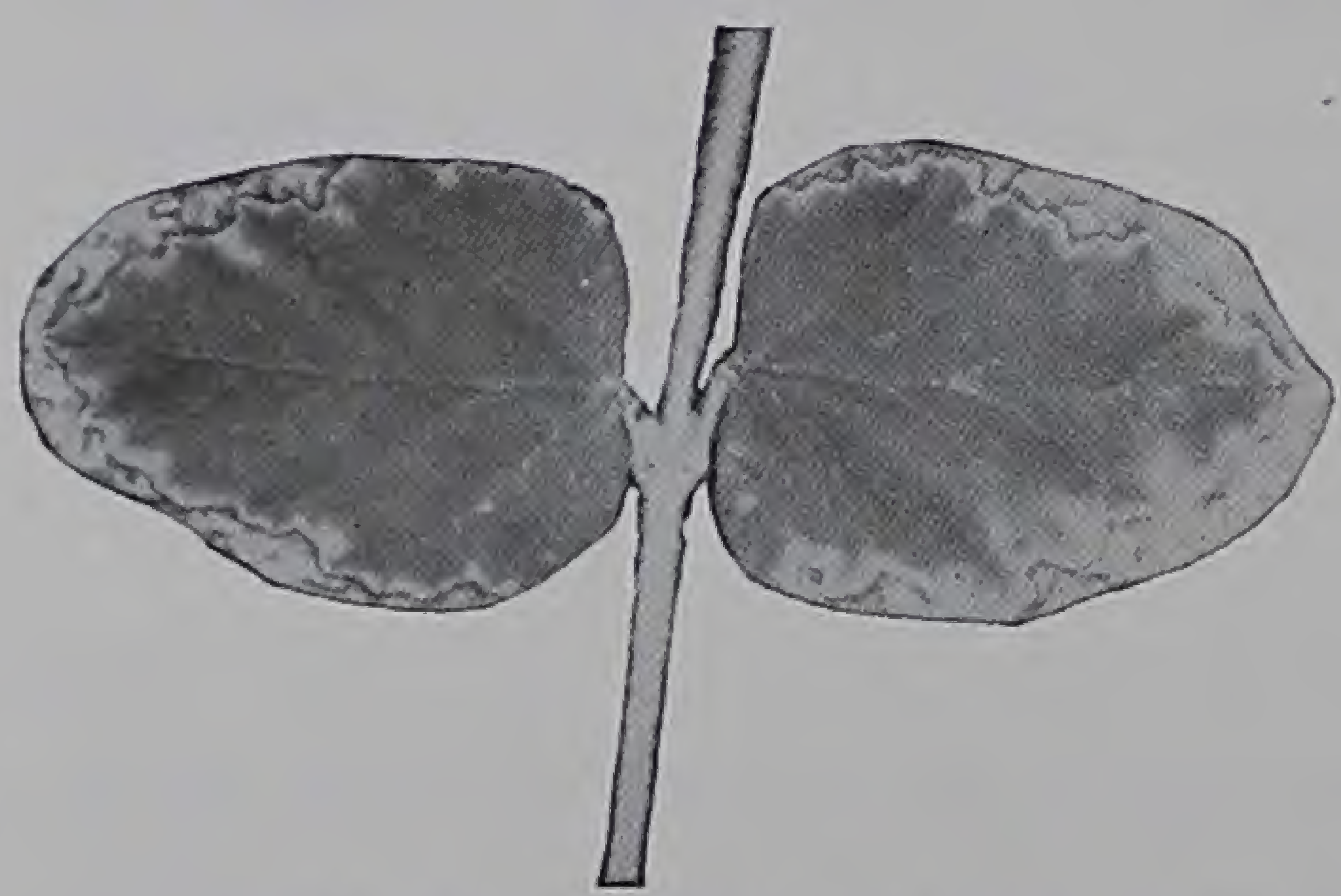
Some reports indicate that a considerable amount of red to purple coloration appears with the yellow. A greenhouse study of the problem in New Jersey showed that high potassium and low boron resulted in red coloration and markedly abnormal growth. Low potassium and low boron resulted in yellowing, less severe abnormality, and a higher boron content in the plants.

Boron-deficiency symptoms in alfalfa appear most abundantly following a period of drought, and may be absent during a season of normal moisture, even though growth is retarded by lack of boron. The extent of the trouble is minimized if observations are made only in seasons of abundant moisture. It is exaggerated if observations are made only following a dry period, when the symptoms are widespread throughout the field. Usually the second and third crops are more severely affected than is the first. If moisture is plentiful, a field of alfalfa that shows pronounced yellowing from boron deficiency one year may show no symptoms whatsoever the next. Boron starvation is so closely related to drought that the yellowing

which is caused by boron deficiency is often attributed to dry weather (12).

Symptoms of boron deficiency in alfalfa have been found to appear before the deficiency limits the yields significantly (15). Boron-deficiency symptoms are a good guide, therefore, in determining when to apply borax. Care must be used, however, in differentiating leafhopper injury from boron deficiency (11).

Boron-deficiency symptoms of Ladino clover are shown first by the leaves' turning yellow (plate 13, page 303). The edges of some of these leaves later become bright red, and then turn brown and die. In Korean lespedeza, red coloration, sometimes with a purplish tint, affects the margins or the tip halves of leaves (plate 14, page 303). The abnormal color spreads over the entire leaf surface, including the veins. The leaf tips that are first affected die, turning first dark brown and later light brown. The symptoms are most marked in the younger portions of the plant, but are distributed over the entire plant. Red and alsike clovers show much the same symptoms.



Courtesy of Department of Agronomy, Ohio State University

Figure 8.—Boron toxicity symptoms in soybeans. The narrow margin around the edge of the leaves fires and is very thin.

Typical boron toxicity, or burn, in young peanut and soybean leaves is shown by the dying of a narrow margin of the leaf edges, with little preliminary yellowing (figure 8). The leaf edge is very thin. Boron toxicity is usually most apparent in young plants but they usually recover from mild cases of burn.

MANGANESE DEFICIENCY

The supply of available manganese in the soil is closely related to the soil reaction. Manganese is more available in acid soils than in those that are neutral to alkaline in reaction.

Manganese deficiency was found in Indiana on soybeans that were growing on soils with a high organic-matter content and a relatively high water-table (41). These soils had pH values of 6.5 or higher. Similar deficiency on certain legumes has been reported on the alkaline organic soils in Michigan. These soils were neutral or alkaline either because of origin or because of the application of too much lime. Soybeans grown on soils high in organic matter along the Atlantic Coast in North Carolina, and in other States, fre-

quently suffer from manganese deficiency at pH values as low as 6.0. In fact, severe manganese deficiency has been observed at pH 5.8.

Manganese deficiency may occur on very sandy soils as a result of overliming. The amount of manganese in such soils is usually very low, because the parent materials may have been low in the element or because it became soluble under the acid soil conditions, and the heavy rains leached it out.

Symptoms

The general symptoms of manganese deficiency in legumes are light green to yellow leaves, with distinctly green veins. Manganese deficiency on soybeans is shown in plate 15, page 304. The areas between the veins over the whole leaf become pale green and then pale yellow. The veins stand out distinctly. In severe cases, brown spots (necrotic areas) appear on the leaves after a few weeks, and the leaves drop off prematurely.

The pattern of manganese deficiency in soybeans differs from that of magnesium in that in magnesium deficiency the veins do not stand out so prominently and the base of the leaf is not affected.

In the field, manganese-deficiency symptoms normally develop first in the younger leaves. After a heavy rain, however, the newly formed leaves may be normal, but the older leaves may remain chlorotic. Excess water may bring about reducing conditions in the soil, and additional manganese may be made available to the plant. Under some circumstances, slight deficiency symptoms may appear early and then disappear. As the roots develop they come in contact with more soil, and the small amount of manganese needed can be more easily obtained. In addition, the roots may penetrate into a more acid soil horizon.

In manganese-deficient peanuts the veins do not stand out as clearly as in the case of soybeans. In the early stages, the chlorosis appears as a pale yellow between the veins. Later in the growing period the chlorosis takes on a definitely bronzed appearance.

Manganese deficiency has been reported on alfalfa and red clover in New Jersey on heavily limed Collington sandy loam (18). The reaction of the surface soil was pH 7.2 and the subsoil pH 6.9. Both crops were very stunted in growth and the leaves showed marked interveinal chlorosis. One week after application of a top dressing of 50 pounds of manganese sulfate per acre, the plants regained their normal color and resumed growth. This instance of

deficiency represents an unusual case, as alfalfa and red clover are crops that are generally considered capable of obtaining sufficient manganese from well-limed soils.

Manganese deficiency can be readily corrected in most legumes by spraying the leaves with a 2 percent solution of manganese sulfate. Normal color will be regained in 3 to 7 days if the trouble is due to a lack of manganese. This method is often used in identifying manganese deficiency.

IRON DEFICIENCY

Although chlorosis due to iron deficiency is not frequently observed in legumes, it may appear on plants growing on calcareous soils (those with free calcium carbonate). Iron-deficient soybeans have been reported in Iowa on a calcareous soil with a pH of 7.9 (28).

There is a close relationship between manganese chlorosis and iron chlorosis (39, 40). Work with soybeans has shown that the iron:manganese ratio is very important. With a low ratio, iron deficiency (manganese toxicity) is developed. With a high ratio, iron toxicity (manganese deficiency) is developed. In the former instance, the addition of iron raises the ratio and the plant resumes normal growth. In the latter instance, the addition of manganese lowers the ratio and the plant also resumes normal growth.

Symptoms

In soybeans, the initial stages are shown by a yellowing and slight curling of the upper leaves, with the veins remaining green (39) (plate 16, page 304). The yellowing continues until the newer leaves, and at times the veins and midrib as well, become almost paper white. For several days, the leaves retain the ability to recover their normal green color on receiving adequate quantities of iron. Soon, however, numerous brown spots of dead tissue (necrosis) appear near the leaf margins. Iron is comparatively immobile in growing plants and is not moved from the older leaves to the younger tissues when a deficiency sets in. Thus leaves that were once green remain so, while the younger leaves become chlorotic.

Peanuts, which were grown in the greenhouse on Sumter and Houston clays that were high in free calcium carbonate, became chlorotic (10). The yellowing disappeared when the plants were sprayed with a dilute solution of ferrous sulfate. Alfalfa on these soils did not become chlorotic.

It is difficult to distinguish between iron and manganese deficiencies during the early stages, since, in both cases, the veins are green. An effective means of identification is to spray one plant with a 1-percent solution of ferrous sulfate and another with a 2-percent solution of manganese sulfate. Normal color should be regained from one or the other of the treatments in 3 to 7 days. The response of iron-deficient soybeans to a ferrous sulfate spray is shown in plate 17, page 305.

COPPER DEFICIENCY

If copper is added to soils, it may serve two purposes. First, it may function as a plant nutrient in soils that are deficient in the element. Second, it may correct certain unfavorable conditions in organic soils. In this capacity, it may favor oxidation processes (46, 47). Soils high in organic matter, particularly new peat soils, have received much attention in this respect. Applications of 30 pounds of copper sulfate per acre on raw peat soils in the Florida Everglades have produced remarkably good responses in soybeans, cowpeas, peanuts, crotalaria, lespedeza and other legumes (3). Responses of subterranean clover and alfalfa to applications of copper have been reported, when grown in sand cultures (33).

Symptoms

Subterranean clover, when grown in sand cultures in the absence of copper, developed light green leaves that were characterized by the absence of the usual dark marking near their centers (33). Many of the plants died, withering suddenly without any symptoms. In alfalfa, there was a tendency for the leaflets to be folded back along the petiole. These leaves withered shortly and the stem tips ceased to grow. Copper-deficient plants look very much like those produced under drought conditions.

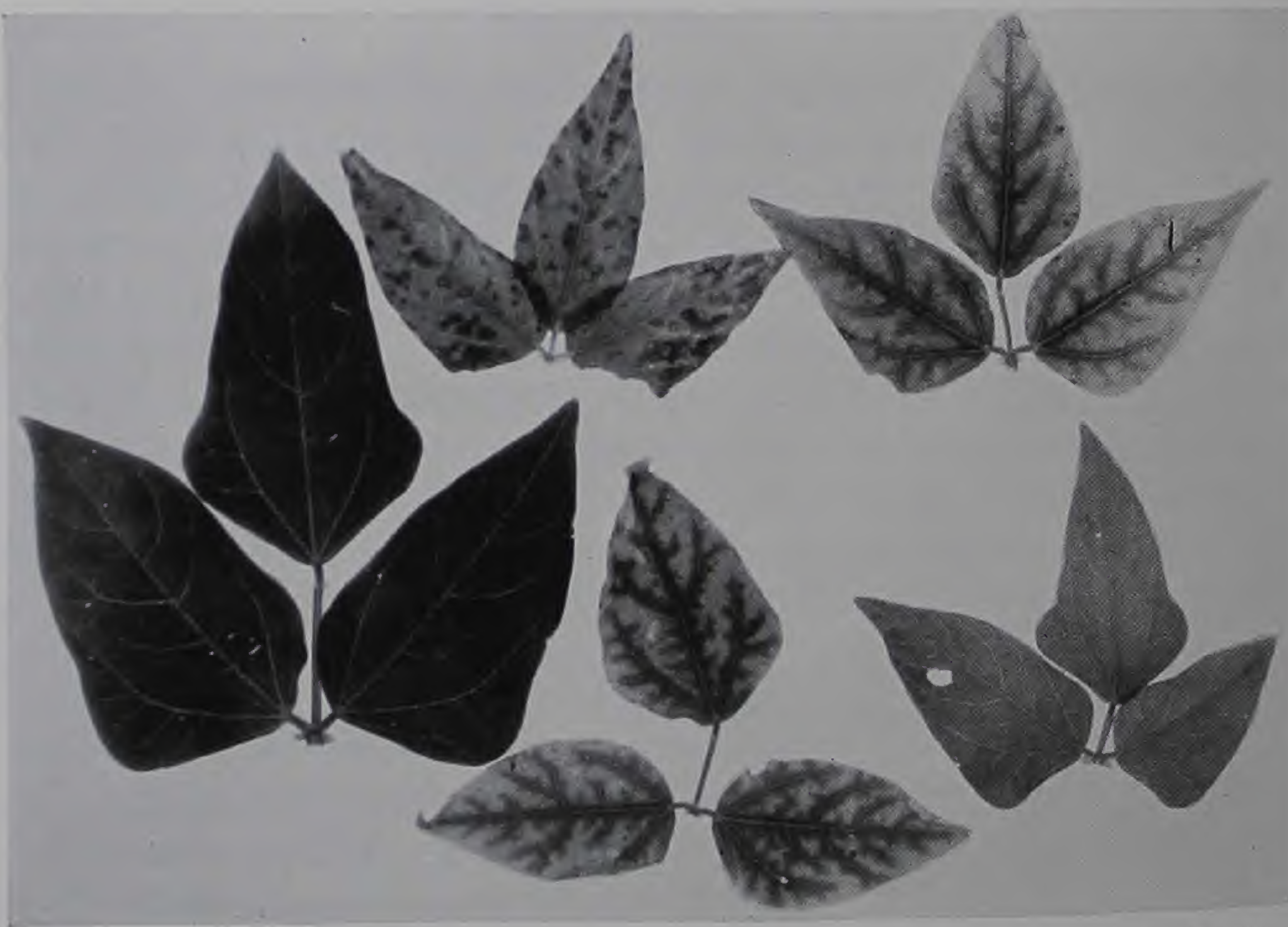
Copper deficiency on legumes that are grown on raw peat soils is characterized by the leaves becoming blotched with yellow and brownish-yellow areas (3). Growth is severely limited, the leaves wither, and excessive shedding occurs.

ZINC DEFICIENCY

Responses of legumes to applications of 20 pounds of zinc sulfate per acre have been reported on sandy soils in central and northern Florida (5). Corn that was grown on these same soils was severely affected with white bud (zinc deficiency). Field responses to appli-

cations of zinc have been obtained on alfalfa and subterranean clover in Australia.

Zinc has been found to be essential for seed production in certain legumes (35). In sand cultures involving the use of purified chemicals, growth proceeded to a certain point, but not far enough for seeds to develop. Lott (24) has shown that the availability of zinc decreases as the soil pH value rises. Above pH values of 6.0 to 6.5, availability is greatly reduced. The availability of zinc to plants is



Courtesy of Citrus Experiment Station, University of Florida

Figure 9.—Zinc deficiency on cowpeas. Left, healthy leaflets. Right, various stages of deficiency. The leaf tissue between the veins becomes yellow and the area along the veins remains green. Zinc sulfate increased yields on this soil.

not entirely dependent on soil reaction, however, since the deficiency is much more prevalent on some soil types than on others.

Symptoms

In Florida, on zinc-deficient soil, cowpeas developed small brown spots on the lower leaves (5). The leaf tissue between the veins then became yellow, with the area along the veins remaining green (figure 9). The tissue in the brown spots died completely, and often the edges of the leaves were dead or crinkled. The leaves fell and were replaced by healthy ones. The plants, however, were

stunted. Velvet beans showed much the same symptoms on this soil. In the same field, peanut yields were increased by an application of zinc sulfate, but there was no visual evidence of malnutrition.

Growth responses from applications of zinc have been obtained on alfalfa grown in specially purified culture solutions (figure 10). In very severe cases, the stems fail to elongate and dieback occurs. The symptoms are very difficult to recognize, however, if zinc-treated plants are not available for direct comparison.

Courtesy of Division of Plant Nutrition, University of California

Figure 10.—Response of alfalfa plants to zinc in specially purified cultures. Each 2-liter beaker had 10 plants growing in a complete Hoagland's culture solution with varying amounts of zinc.

MOLYBDENUM

Responses of legumes to molybdenum applications in the field have not been reported in the United States (21). On a South Australian ironstone soil, however, herbage legumes have shown considerable response to small applications in the field (4). Amounts on the order of 1 ounce molybdenum oxide per acre were adequate. The effects on subterranean clover have received considerable attention. Grasses did not show much response. A large part of the benefit from molybdenum appears to be due to its stimulating effect on the nodule bacteria. Work with Azotobacter and Rhizobium, in

purified cultures, has shown that additions of molybdenum multiply nitrogen fixation several fold (27). Applications of molybdenum increased the nitrogen content of alfalfa in New Jersey from 2.88 to 3.08 percent, as an average of five cuttings over a 2-year period. The yield increase was not significant, however. Care must be taken in using additional molybdenum, since the element tends to be toxic to animals.

Symptoms

In pot experiments, using the ironstone soil mentioned above, sodium molybdate, at the rate of 2 pounds per acre, doubled the yield of alfalfa (4). The leaves of untreated plants were yellowish to pale green while the treated plants were dark green. This chlorosis is largely a result of a low-nitrogen content.

INSECT DAMAGE

Considerable care must be exercised in diagnosing nutrient-deficiency symptoms if they are not to be confused with insect damage (plate 18, page 305). Leafhopper damage is especially confusing. The leafhopper punctures the midrib of the leaf, and the resulting yellow or red discoloration is in the form of a "V," the apex of which represents the point of feeding (plate 18, left). In alfalfa, this "V" type of yellowing or reddening provides one of the best means of recognizing leafhopper injury.

Spots that are caused by the garden flea beetle on alfalfa may sometimes be mistaken for the beginning of potash deficiency. Yellowing does not develop between the spots, however.

Thrip damage often gives rise to peculiar malformations on peanuts early in the growing season (plate 18, right). In late May and early June, in North Carolina, a flood of inquiries is received asking "What's wrong with my peanuts?" Applications of DDT usually solve the problem.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS OF LEGUMES

Symptoms	Element deficient
I. Effects general on entire plant or confined to older or lower leaves.	
A. General on whole plant; also yellowing and drying up or firing of lower leaves.	
1. Plant light green. Lower leaves affected first but other leaves soon follow. Lower leaves fade to pale yellow then brown with later shedding. Stunted growth. Due to lack of nitrogen fixation by bacteria.	Nitrogen
2. Plant dark green. Petioles and leaflets tilted upward. Plants spindly and stunted. The stems may turn red.	Phosphorus
B. Localized, occurring as mottling or chlorosis with or without spots of dead tissue on lower leaves; little drying up of lower leaves.	
1. Areas between main veins become pale green which later turns deep yellow. The base and lower center of the leaf are not affected. Deficiency appearing at a late stage of growth is shown by a downward curling of leaf margins, a gradual yellowing from the margin inward and bronzing.	Magnesium
2. Yellow mottling around the edges of the leaf. Chlorotic areas merge forming a rather distinct, continuous yellow border around the tip end and along the sides of the leaf. This area soon dries and the dead tissue falls out. In small-leaved legumes there is a tendency for leaves on all parts of the plant to be affected, with small white spots appearing around the leaf margins first. Stunted growth.	Potassium
3. Brown spots develop with yellowing of the leaf tissue between the veins. Dead tissue drops out of chlorotic areas. Stunted growth.	Zinc
II. Effects localized on newer leaves of plant—Stunted growth.	
A. Terminal bud dies following distortions at the tips or base of young leaves.	
1. Leaves near the growing point are yellowed and sometimes reddened. Lower leaves remain healthy green color. Internodes shortened forming a rosette. Buds appear as white or light brown dead tissue. Little flowering.	Boron
B. Terminal bud remains alive.	
1. Light green to yellow leaves with all veins remaining distinctly green. Spots of dead tissue appear on the leaf. Heavy rains may cause chlorosis in young leaves to disappear.	Manganese
2. Leaves yellow to almost white with principal veins remaining green. Spots of dead tissue appear particularly at the leaf margins. Tissue drops away.	Iron
3. Leaf including veins turns pale green to yellow. Young leaves affected first.	Sulfur
4. Young leaves may wilt and wither without chlorosis. Excessive leaf shedding occurs.	Copper

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Courtesy of Department of Agronomy, University of Illinois

Plate 1.—Symptoms of nitrogen deficiency appear in uninoculated soybeans growing in a soil which does not contain the appropriate nitrogen-fixing nodule bacteria. Note the pale green to yellowish color and the lower height of the plants in the uninoculated check strip.

Courtesy of Division of Soil Management and Irrigation, BPISAE

Plate 2.—The proper nodule bacteria must be present in order to secure good growth of a legume. The white clover in both pots was inoculated. Right, a poor strain of bacteria was used; note the yellow and dying plants. Left, an efficient strain of bacteria was used; note the healthy green plants.

Courtesy of U. S. Regional Soybean Industrial Products Laboratory

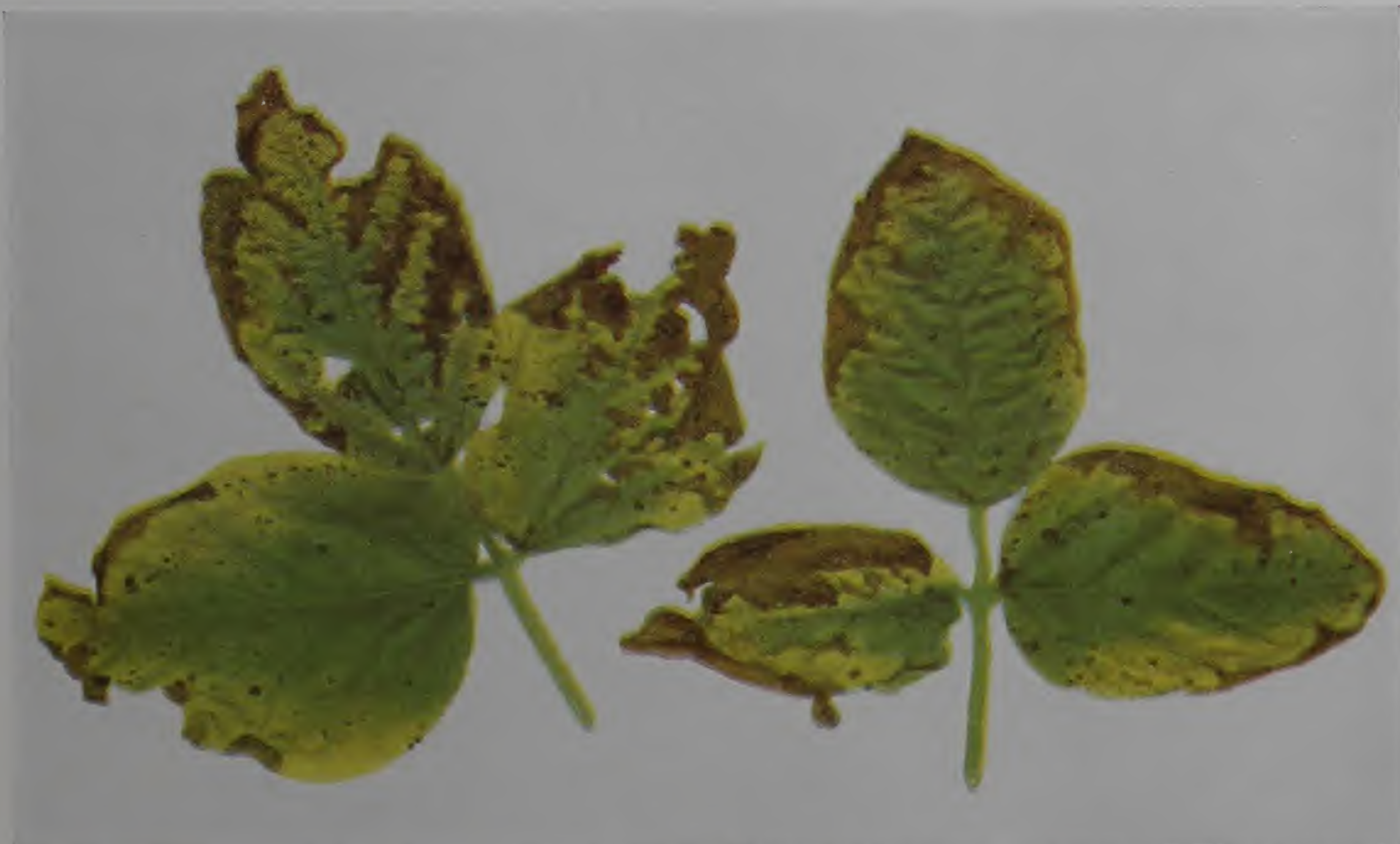
Plate 3.—Soybean leaves showing progressive stages of nitrogen deficiency. The plants were grown in gravel culture under controlled condition.

Courtesy of Department of Agronomy, North Carolina State College

Plate 4.—Growth response of soybeans to phosphorus. Left, no P_2O_5; right, 40 pounds of P_2O_5 per acre. In the field increased growth is the most prevalent response of legumes to phosphorus.

Courtesy of Agronomy Department, University of Illinois

Plate 5.—Potassium-deficiency symptoms in soybean leaves, early stages. Chlorosis begins with yellow mottling, then forms a continuous band along the sides and tip end of the leaf.



Courtesy of Agronomy Department, University of Illinois

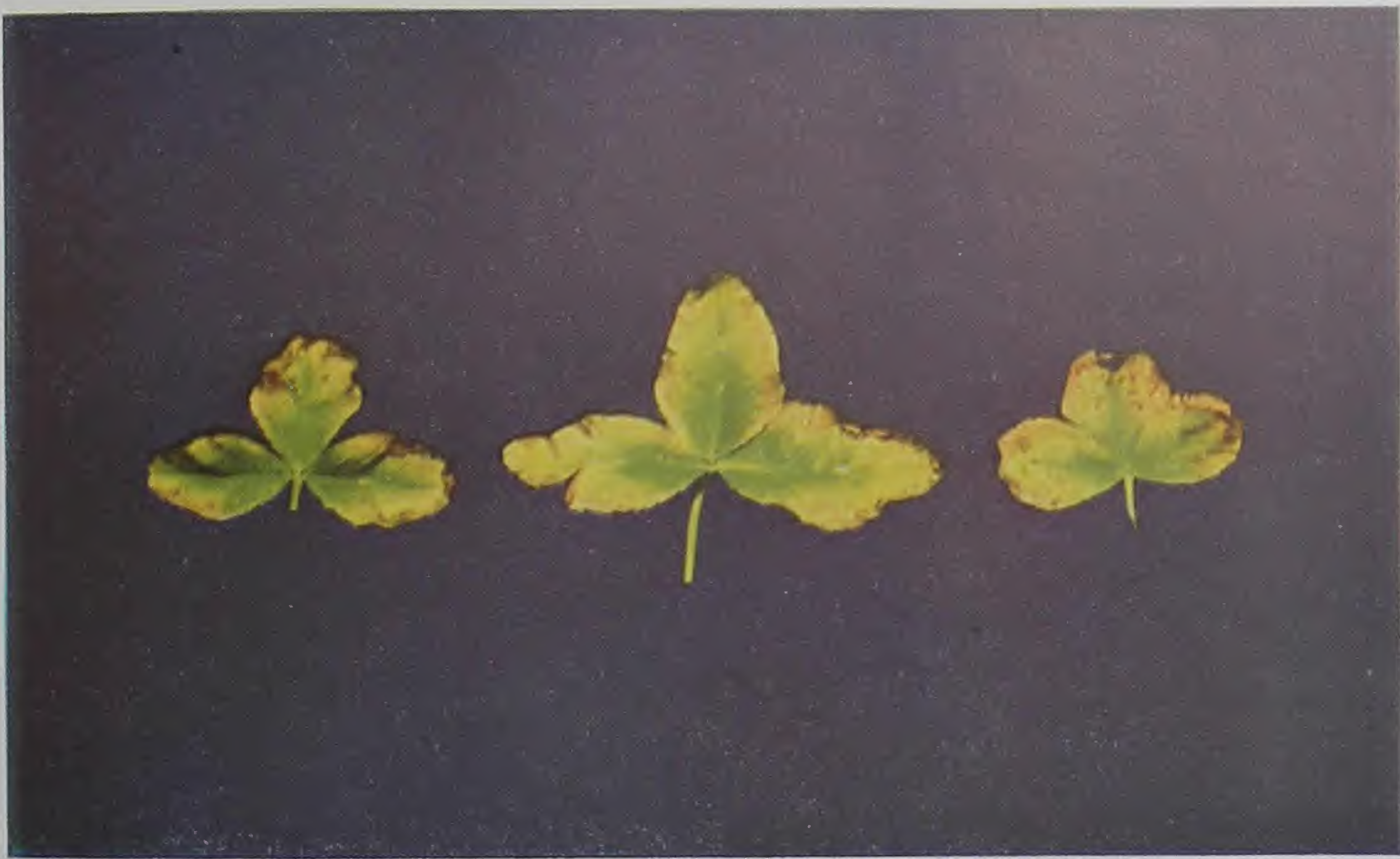
Plate 6.—Potassium-deficiency symptoms in soybean leaves, advanced stages. The chlorosis proceeds inward and the margins of the leaves fire to a medium brown color. The center of the leaf may still be green after the margin is completely dead.

Courtesy of American Potash Institute, Inc.

Plate 7.—Alfalfa plants exhibit symptoms of potassium deficiency very similar to those observed in red clover. Chlorosis appears first as small dots; then it involves the entire leaf margin and is followed by death of the tissues, which turn brown. The edges of the leaves become broken and ragged in the more advanced stages.

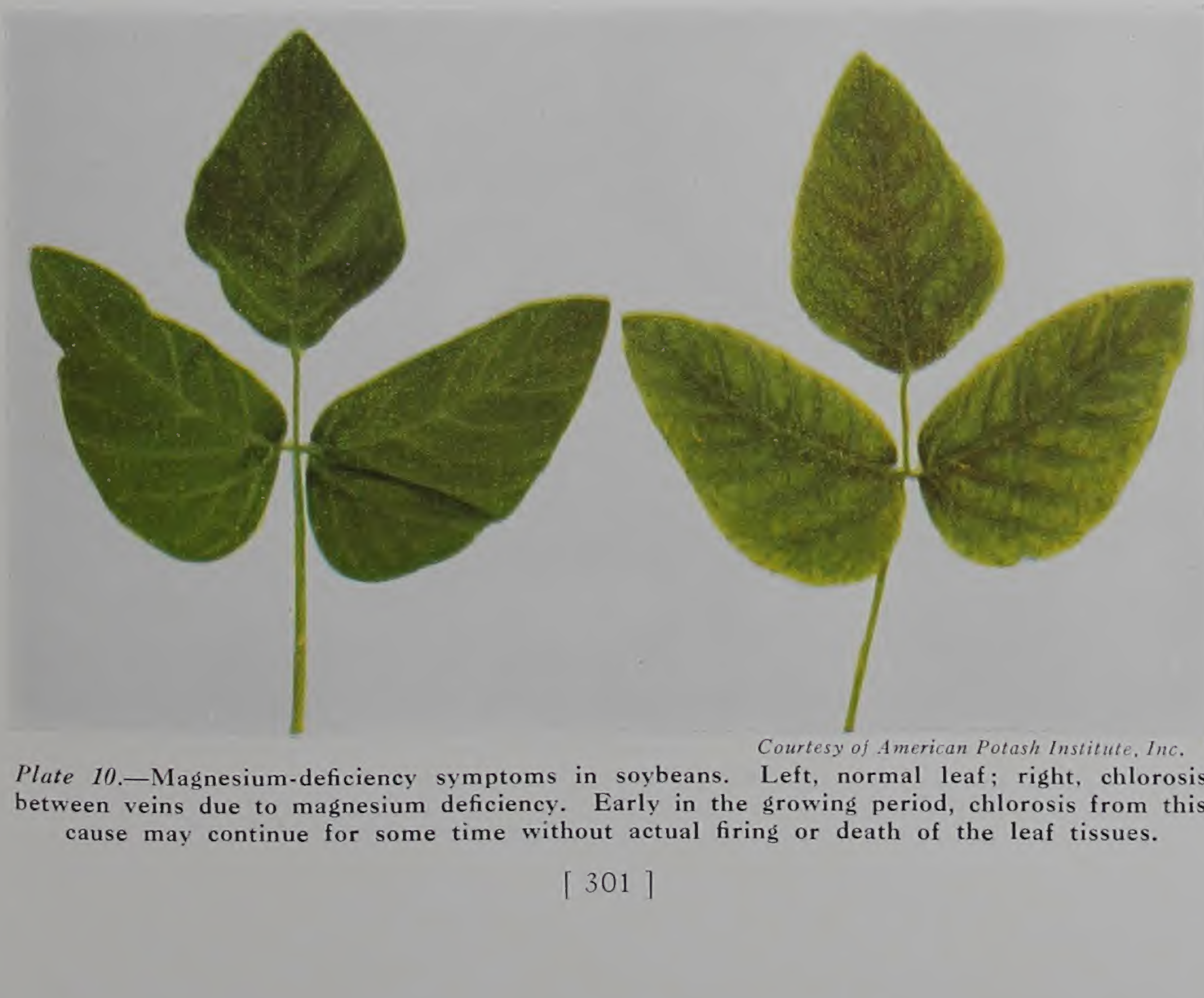
Courtesy of Division of Soil Management and Irrigation, BPISAE

Plate 8.—Potassium-deficiency symptoms in Ladino clover. The most characteristic symptoms are small yellow spots appearing near the edges of the leaflets, with these edges later turning yellow. With leaflets showing severe deficiency, the entire surface with the exception of the area near the midrib may be affected.



Courtesy of American Potash Institute, Inc.

Plate 9.—Alsike clover does not differ appreciably from alfalfa and Ladino clover in the general appearance or detailed pattern of potassium-deficiency symptoms.



Courtesy of American Potash Institute, Inc.

Plate 10.—Magnesium-deficiency symptoms in soybeans. Left, normal leaf; right, chlorosis between veins due to magnesium deficiency. Early in the growing period, chlorosis from this cause may continue for some time without actual firing or death of the leaf tissues.

Courtesy of Department of Agronomy, North Carolina State College

Plate 11.—Magnesium deficiency in crotalaria. A broad margin of the leaf turns yellow, the base and center of the leaves remaining green. There is a tendency for the veins to remain green.

Courtesy of Department of Agronomy, North Carolina State College

Plate 12.—Boron-deficiency symptoms in alfalfa. The leaves near the growing point are yellowed but sometimes have a reddish tinge. The lower leaves remain a healthy color. In severe deficiency the flowers fail to form and the buds appear as white or light brown dead tissue.

Courtesy of Department of Agronomy, Purdue University

Plate 13.—Boron-deficiency symptoms in Ladino clover. The margins of the leaves are first yellowed and then take on a reddish tinge. The edges of the leaves later turn brown and die.

Courtesy of Department of Agronomy, University of Illinois

Plate 14.—Boron-deficiency symptoms in Korean lespedeza. Red coloration affects the margins of the tips of the leaves. The tip end fires and tends to split.

Courtesy of Department of Agronomy, North Carolina State College

Plate 15.—Soybean leaves showing manganese deficiency. The areas between the veins over the whole leaf become pale green and then pale yellow. The veins stand out very distinctly. Eventually brown spots appear on the leaves and the leaves are shed. Manganese-deficiency symptoms are very difficult to distinguish from those of iron.

Courtesy of American Potash Institute, Inc.

Plate 16.—Iron chlorosis in soybeans grown on a calcareous soil. The areas between the veins turn yellow with the veins remaining green. Later the newer leaves, sometimes including the veins, become almost paper white.

Courtesy of Department of Agronomy, Iowa State College

Plate 17.—Response of iron-deficient soybeans to ferrous sulfate spray. The row on the right showed marked recovery within 10 days after being sprayed with 1.0 percent ferrous sulfate solution at the rate of 10 pounds per acre of $Fe\,SO_4 \cdot 7\,H_2O$. The application was repeated after 3 weeks. The treated beans yielded 30.8 bushels as compared to 11.6 bushels where no iron was applied. (Harpster silty clay loam pH 7.9).

Courtesy of Department of Agronomy, North Carolina State College

Plate 18.—These symptoms are not signs of nutrient deficiency. Left, leafhopper injury on crotalaria. Note the characteristic yellow "V" at the tip end of the leaves. This is often rather widespread in peanuts. Right, thrip injury in peanuts. This type of malformation occurs rather early in the growing period.

CHAPTER IX

Symptoms of Citrus Malnutrition

By A. F. Camp, H. D. Chapman and E. R. Parker[1]

THE use of specific symptoms as guides to the nutritional needs of citrus trees, which has been common for many years, probably had its inception in the use of copper compounds to correct the symptoms of dieback or exanthema. In fact the use of the symptoms involved in dieback as a guide to copper applications preceded any very clear understanding of the role of copper. As knowledge of the field has developed, the symptoms of zinc, manganese, iron, boron, magnesium and nitrogen deficiencies have been described and used as general diagnostic characters with notable success. The symptoms of these deficiencies fortunately have been quite definite and easily recognizable, so that in the hands of the citrus grower the information has been of great value as a guide to the nutritional needs of the tree.

Mineral deficiencies have been much more widely distributed in Florida than in California or other citrus-growing areas because of the very light and acid soil and heavy leaching rains. Because of these and other factors, deficiencies developed soon after extensive areas of these light sandy soils were planted to citrus; and copper, zinc, manganese and magnesium have become generally used in commercial practice in addition to the commonly used nitrogen, phosphorus, calcium and potassium. Although mineral deficiencies are less common in citrus areas other than Florida, zinc and mild manganese deficiencies are widespread in California, and copper deficiency, though less common, is likewise well known. Iron deficiency is also quite common in California and Arizona, being severe under certain soil conditions. In many citrus areas the alkalinity of the soil, which results in the formation of insoluble compounds of many of the elements needed by the citrus tree, seems to be a contributing factor.

In the succeeding discussion particular attention is given to deficiencies which occur commonly in the field and the symptoms of which are used as a guide in fertilizing practices. Symptoms known

[1] A. F. Camp is vice director, Florida Agricultural Experiment Station, in charge Citrus Experiment Station, University of Florida; H. D. Chapman is professor of soils and plant nutrition and chemist in the Experiment Station, chairman of the Division of Soils and Plant Nutrition, University of California Citrus Experiment Station; and E. R. Parker is horticulturist in the Experiment Station and chairman, Division of Orchard Management, University of California Citrus Experiment Station. George M. Bahrt, formerly soil technologist, Soil Fertility Investigations, Bureau of Plant Industry, U. S. Department of Agriculture, co-author of this chapter in the original edition, has passed away since publication of that edition.

only from water and sand culture studies are discussed in less detail. A key at the end of the chapter summarizes deficiency symptoms for ready identification and reference.

BORON DEFICIENCY

Boron deficiency of citrus has been definitely identified in the field in Rhodesia, South Africa, where it was described in detail by Morris (51, 52), and in Florida where it was described by Camp (9) and Camp and Fudge (12). Though its occurrence in the field is limited, boron deficiency has been studied extensively both in water culture and in large tank soil cultures. Such studies were first reported in California by Haas, and later the anatomical and physiological features of the deficiency were described by Haas and Klotz (45). Later Chapman and Kelley (23) produced boron deficiency in orange trees growing in drums filled with a granitic soil. Recently Haas has reported (41) further descriptive symptoms on plants grown under controlled conditions. Morris did not find in the field all of the symptoms reported from water culture, but the symptoms produced in the above-mentioned drum experiments agreed in general with those of Morris save that a few leaves showed vein splitting. However, this was not a conspicuous symptom as was the case with seedlings or cuttings grown in the greenhouse. Boron deficiency is known in Rhodesia as "hard fruit" because of the lumps in the rind caused by gum impregnations, and this is the primary symptom seen in Florida.

Symptoms

Morris reported that boron deficiency in the field was characterized by small water-soaked spots or flecks in the leaves, the spots becoming translucent as the leaves matured (figure 1). There was a premature shedding of leaves resulting in severe defoliation. He pointed out that the first symptom was a premature wilting of the trees which appeared to be out of proportion to the available supply of water, and that the leaf symptoms reported above were apparently subsequent to the wilting. The chief leaf symptom reported by Haas and Klotz as characteristic of boron deficiency in cultures was an enlargement of the veins, accompanied by a splitting and corking of the upper surface of the veins.

Morris reported, however, that corking of the veins was not characteristic of boron deficiency in the field in Rhodesia. Accompanying the leaf symptoms is a dying back of the trees and a bushy upright growth similar to that occurring in zinc deficiency. The leaf

symptoms and the wilting have not been seen in the field in Florida though an unthrifty growth has been observed.

The chief fruit symptoms in the field reported by Morris include premature shedding of young fruits. Such fruits had brownish discolorations in the white portion of the rind (the albedo), described commonly as gum pockets but more accurately as impregnations of the tissue with gum, an unusually thick albedo, and a peculiar "feel" on cutting, as though cheesy instead of normally crisp (figure 2).

Courtesy of California Agricultural Experiment Station

Figure 1.—This picture shows translucent spots on young lemon leaves, one of the symptoms of boron deficiency.

Older fruits were misshapen, with an unusually thick albedo containing gum deposits, seed failed to develop, and gum deposits were common around the axis of the fruit (plate 1, page 355). Affected fruits were unusually hard and dry, and the small amount of juice obtainable by hand squeezing was low in sugars. Subsequent to Morris' report, Chapman and Kelley (23) and later Haas (41) reported the finding of similar fruit symptoms on trees growing in cultures.

Fruit symptoms similar to those reported by Morris in Rhodesia were reported by Camp in Florida, and the occurrence of boron deficiency in citrus has become fairly common. This has apparently been associated with the excessive use of dolomitic lime which has had an adverse effect on the availability of boron. The occurrence

of symptoms has also been associated with drought conditions during the spring when the young fruit is developing. In years of heavy spring rainfall the symptoms are less commonly found. The situation is complicated in the case of grapefruit by the fact that when arsenic is used to reduce the acid content of the fruit similar fruit symptoms may develop which are indistinguishable from those due to boron deficiency. Whether arsenic has an effect on the utilization

Figure 2.—Young fruit from boron-deficient orange trees showing dark resinous areas in the albedo and lesions on the peel.

Courtesy of California Agricultural Experiment Station

of boron or whether these are parallel symptoms has not been determined.

Boron deficiency has not been identified in California citrus soils but some irrigation waters there contain sufficient boron to cause symptoms of excess on citrus trees.

Cause and Treatment

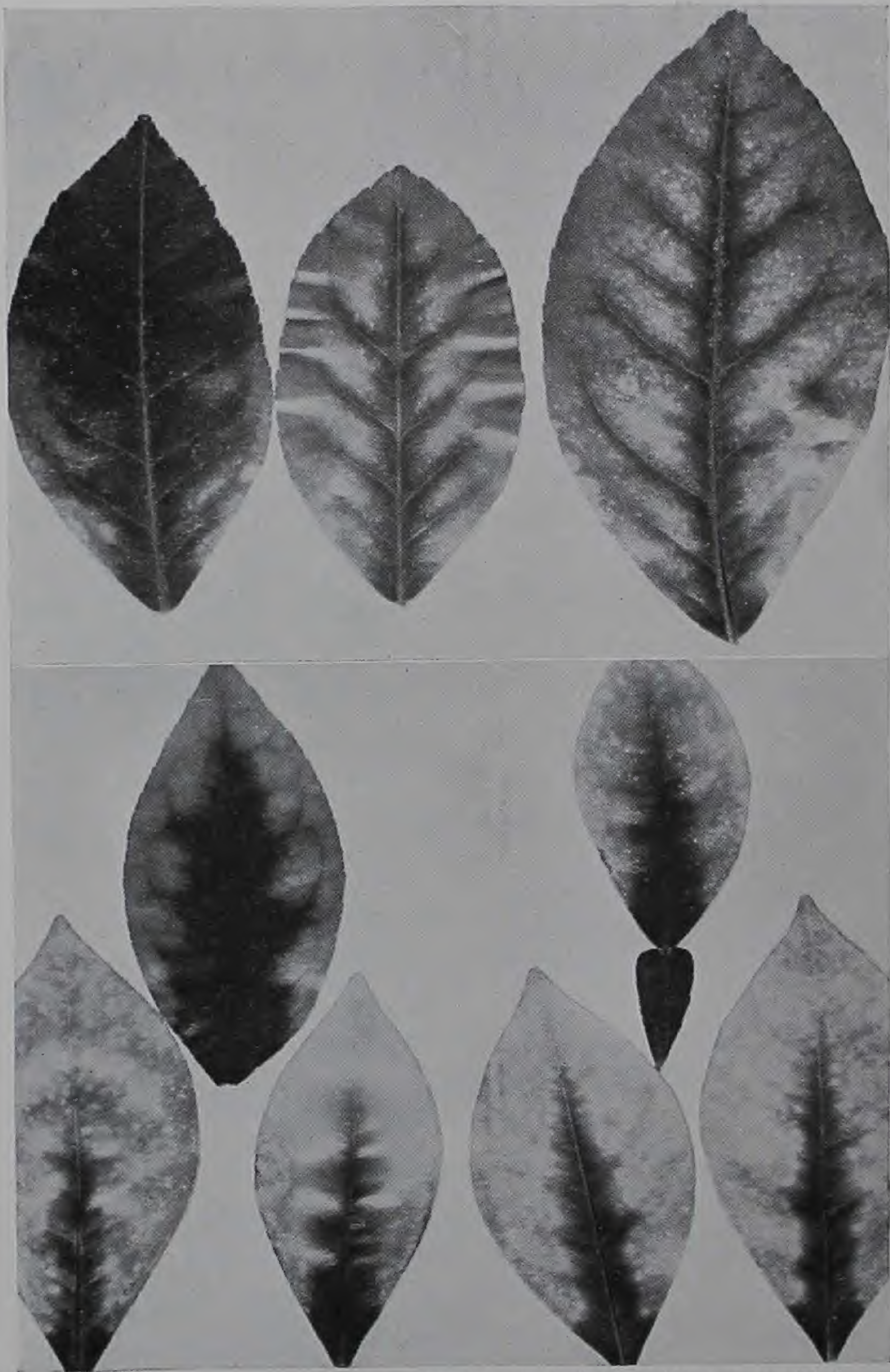
No cause for boron deficiency is given by Morris, but he reports excellent results from soil applications of boron followed by irrigation. Spray applications have been found much safer and more satisfactory in Florida than soil applications because the soil applications frequently fail to give satisfactory results during dry springs and may result in toxicity if made during the summer rainy season.

CALCIUM DEFICIENCY

Calcium deficiency has never been reported from the field, and it appears rather doubtful that it will develop on the soils commonly used for citrus. On very acid sands in Florida, available calcium may be so low as to result in an unusually large intake of potassium, but results from applications of calcium have not been obtained except as they were associated with the use of limestone for the correction of acidity and unfavorable base-saturation conditions of the colloidal complex in the soil. Under such conditions lime has given a response by producing more favorable soil-fertility conditions, but the use of other calcium sources which did not materially affect the reaction of the soil failed to produce any result that would indicate a condition of calcium deficiency. This was true even though the level of calcium in the soil was theoretically so low as to affect soil fertility adversely. The alkaline soils of California are well supplied with calcium, and irrigation waters in that State also provide this element. Symptoms of calcium deficiency have been reported from sand cultures by Reed and Haas (65, 66, 67) in California, and further information from similar sources has been developed by Chapman and Kelley (23).

Symptoms

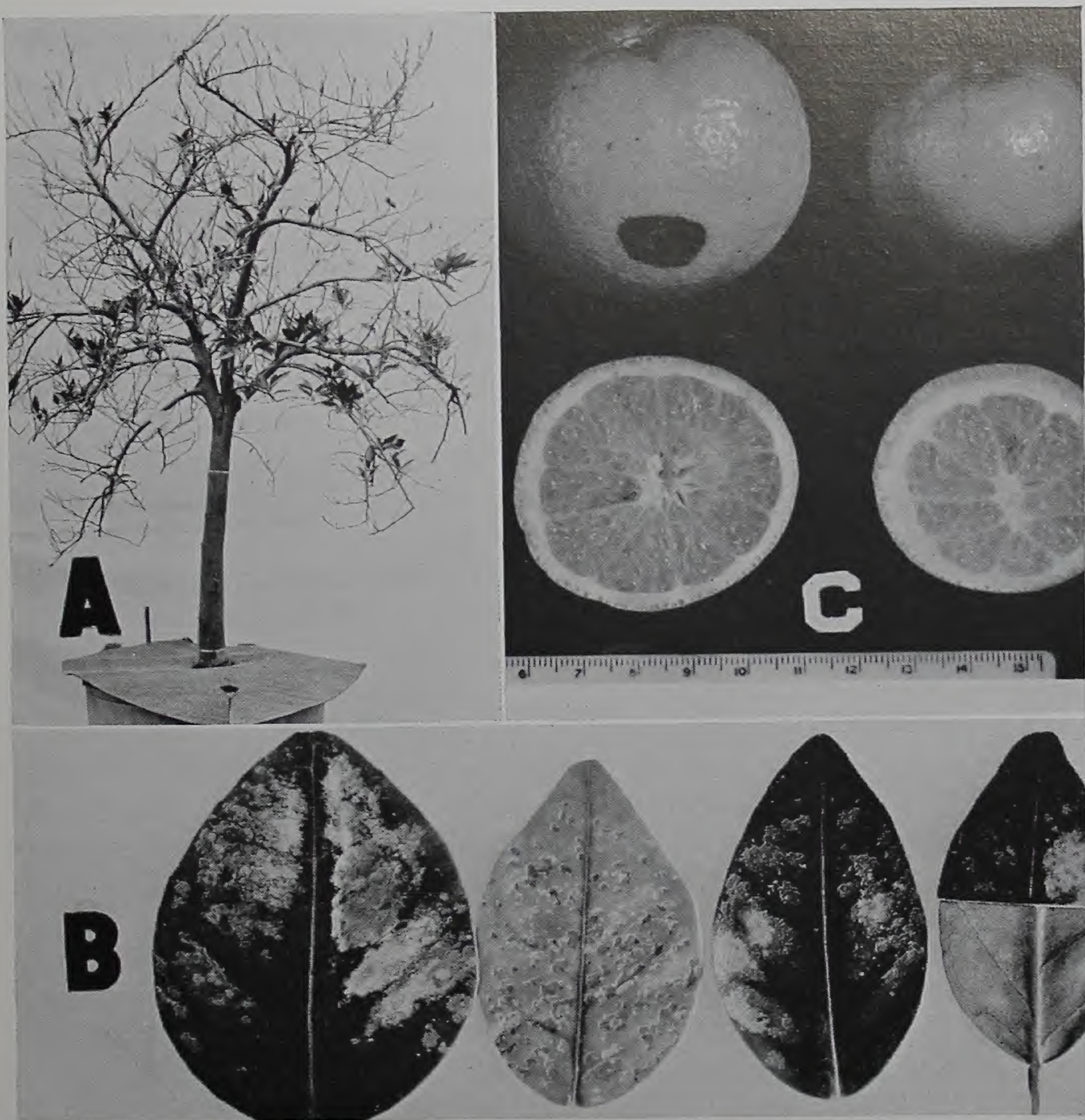
Some of the early culture work of Reed and Haas is difficult to evaluate, since the so-called vein chlorosis, in which the veins fade to a much lighter color than the surrounding tissue, is reported as a symptom, whereas it may be due to rotting of the roots. This symptom, which will be discussed in more detail under nitrogen deficiency, is the common result of girdling, damaged root systems, or other conditions which reduce mineral intake and disrupt the transfer of nutrients in the plant. Omitting this as a definite diagnostic symptom, it was found that leaves on calcium-deficient trees in sand culture developed a fading of the chlorophyll along the margins of the leaf and between the main veins (figure 3). Small necrotic (dead) spots developed in the faded areas, and in the case of lemon leaves these developed into larger burned areas (plate 2, page 356). There was a premature shedding of these leaves followed by the development of additional leaves which also fell prematurely. The twigs died back from the tip, and weak shoots developed from the lateral buds but these soon died. In later work with bearing orange trees grown in solution cultures out of doors, it was found by Chap-



Courtesy of California Agricultural Experiment Station

Figure 3.—Calcium-deficiency symptoms on leaves of lemon (top row), grapefruit (middle row), and sweet orange (bottom row). Note the yellowing of areas of internal tissue (mesophyll) and the peppering of small necrotic (dead) spots. The symptoms are from trees in sand cultures, since calcium deficiency has never been reported in the field.

man (unpublished) that the leaf symptoms illustrated and described above were produced only when potassium was high. When magnesium was high the trees were not characterized by as much dieback, but the leaves gradually turned yellow and a tree condition somewhat similar to nitrogen deficiency developed. The fruits produced were undersized and somewhat misshapen, and the juice vesicles were often shriveled and the contents gelatinized. See figure 4 for additional tree, leaf and fruit symptoms.



Courtesy of California Agricultural Experiment Station

Figure 4.—Calcium-deficiency symptoms on Valencia oranges grown out of doors in sand cultures: *A*, showing extreme defoliation and dieback of tree supplied with high potassium; with high magnesium and low potassium defoliation was not nearly as severe. *B*, leaf necrosis of upper side of leaf under conditions of potassium excess; the underside of the leaf was not affected; leaves from trees supplied with high magnesium and low potassium showed no such burn. *C*, fruit from calcium-deficient tree showing small size, and partially gelatinized and shriveled juice vesicles. The tree from which this fruit came was supplied with a low level of potassium and high magnesium. Fruit from calcium-deficient, high-potassium trees was large with a very coarse rind texture, in contrast to that shown here.

COPPER DEFICIENCY

Copper deficiency is widespread in Florida and occurs frequently in California. "Dieback," the name by which it is commonly known in Florida, has been reported from other citrus-growing areas, but

the use of the term makes the accurate interpretation of some of the reports difficult, and in many cases the dying back is the result of other causes. Copper deficiency is apparently neither so common nor so serious in other areas as it is in Florida. In that State it is also known to growers as "ammoniation," "red rust" or "exanthema." The symptoms were first described from Florida in 1875 by Fowler (33), who considered the deficiency a fungus disease. In 1917, Floyd (32) in Florida described the symptoms in detail very much as they are recognized today. The origin of the use of copper as a corrective is obscure, but Floyd (31) reported successful results from the use of bordeaux sprays in 1913, and Grossenbacher (36) reported successful results from soil applications of copper sulfate in 1916. The origin of the practice of inserting bluestone crystals under the bark is unknown. Although the use of copper as a corrective was common in both Florida and California, the trouble was not generally recognized as a copper deficiency until after successful work on zinc deficiency, which tended to clarify the situation.

Symptoms

The first evidence of mild copper deficiency is the occurrence of unusually large dark-green leaves on long, soft, angular shoots, the leaves being commonly of irregular contour, usually with a "bowing up" of the midrib. The soft twigs sag at the tips or become S-shaped. In this stage the tree appears to the casual observer as unusually vigorous, although in California this excessive growth is not so prominent. When the deficiency is more acute, very small leaves may develop and quickly shed on twigs that are going to die back, but on the older wood the leaves will be large, dark green, and somewhat twisted or malformed. This peculiar twisting and malformation of foliage is particularly common on copper-deficient grapefruit trees. In very acute cases the leaves may be greatly distorted, the margins irregular, and the color light green with a fine network of darker green veins. In such cases the growth of the twigs is restricted, fine and very angular.

Following the appearance of the initial symptoms the affected twigs usually show a development of multiple buds. These produce a dense, somewhat bushy growth, particularly in lemon trees of moderate vigor. Occasionally gum pockets develop between the bark and the wood. These may rupture the bark and permit the gum to exude. In dry weather the gum collects and dries on the surface of the bark. However, it is readily soluble in rain water

and frequently is overlooked for that reason. As the deficiency becomes more acute, new growth develops and then dies back for several inches (plate 4, page 357). In very acute cases heavy twigs having multiple buds put out a profusion of young soft shoots with small leaves which quickly die back from the tips. In this stage the twigs have a reddish excrescence over a large portion of the bark. Neither the dying back nor the reddish excrescence is so pronounced

Courtesy of Florida Agricultural Experiment Station

Figure 5.—Pineapple orange tree (left) affected with acute copper deficiency showing dying back of new growth and very large foliage on water shoots; tree (right) of same age and with same fertilizer treatment except that it has received applications of copper sulfate.

in grapefruit as it is in oranges, and it is still less obvious in tangerines. As the acute stage is reached there is a pronounced loss of growth due to dying back, and in very serious cases the tree may be almost killed (figure 5). The dying starts on the outer shoots of the tree; soon the characteristic large soft shoots appear as water sprouts on large branches in the center of the tree, and these in turn develop the characteristic symptoms. In acute stages gumming has been found in the roots also, and considerable loss of roots takes place.

In cases of severe copper deficiency the fruit is marked irregularly with reddish-brown excrescences, which are light-colored on young fruit but progressively darken until they may be black on mature fruit (plate 5, page 358). Young fruits are sometimes bumpy and

generally have an unusually light green color and a very smooth skin with or without the light reddish-brown excrescences. By June some of the fruits will be almost covered with these excrescences and drop from the tree. Such fruits as are left usually have juice low in acid and very insipid, and the pulp dries out early in the season. In such acute cases there are gum pockets in the rind and gum at the axes of the segments; splitting of young fruits is common and includes both the ordinary longitudinal splitting which starts at the stylar end and transverse splitting which starts in an excrescence and extends part way around the fruit.

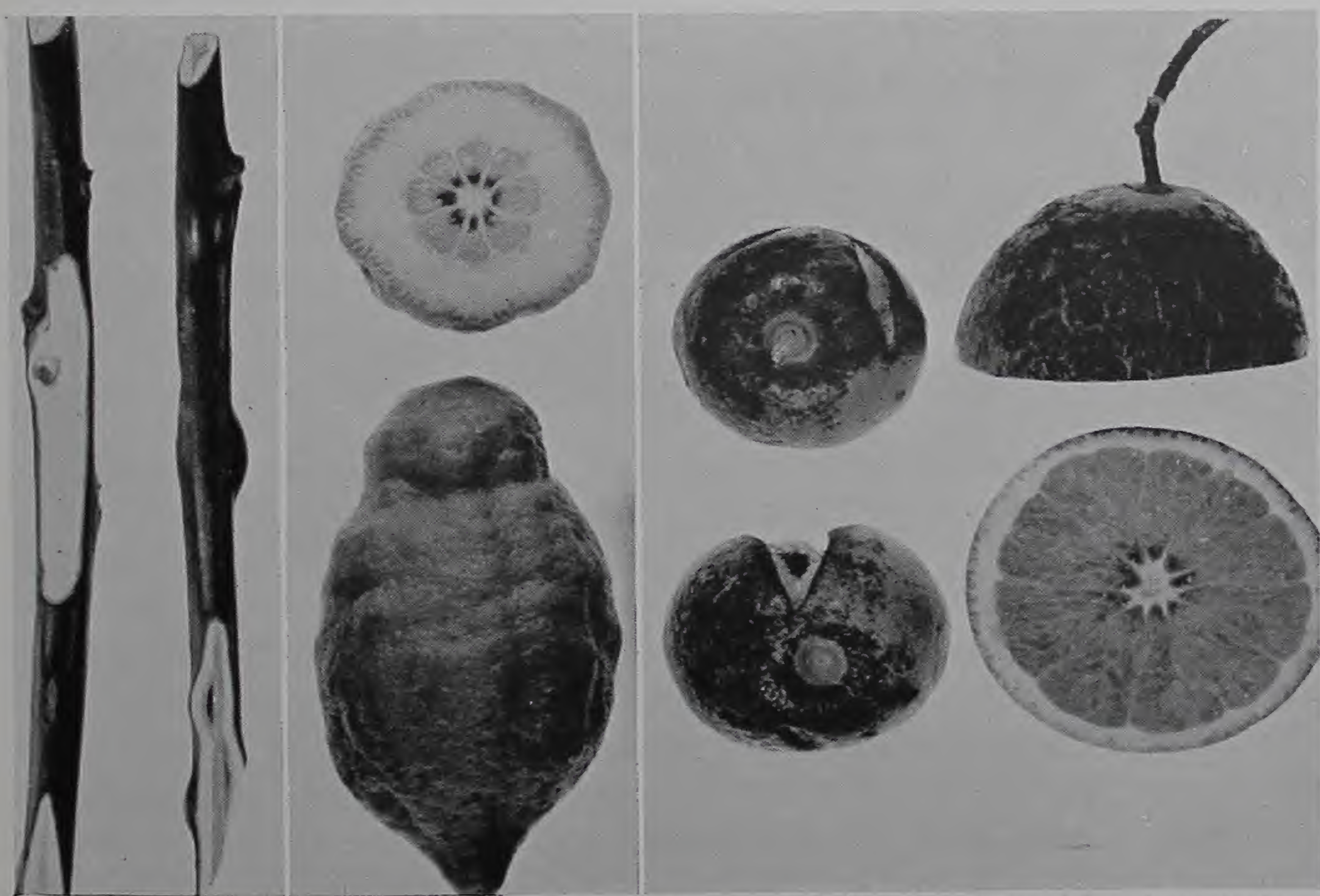
The symptoms described are typical of oranges. In grapefruit the excrescences on the peel are less common, and though gum pockets are numerous in the rind, gum is seldom found around the seeds. Fruits from copper-deficient grapefruit trees are commonly yellower than normal and are frequently lopsided, and as they mature brown pits develop in the rind that are similar to storage pits but smaller. Acute copper deficiency is uncommon in grapefruit and seldom observed in tangerines.

Acute deficiency of copper may put trees entirely out of production, while in the intermediate stage there is a reduction in yield and also considerable loss due to lowered grade of the fruit.

Copper deficiency tends to reduce the soluble-solids content and also the acid content of orange juice. Since the reduction in acid tends to be disproportionate to the reduction in solids the fruit from deficient trees tends to have a higher ratio of solids to acid. The vitamin C content of the juice is also reduced, more or less in proportion to the reduction in acid. It is interesting to note that this reduction in solids and acid and also vitamin C varies with different varieties as it relates to the occurrence of other symptoms. The Hamlin variety of orange may show a very high reduction in solids and acid with very few of the visible morphological symptoms, whereas in other varieties the extent of the symptoms more or less parallels the reduction in the soluble constituents of the juice.

Zinc deficiency is commonly associated with copper deficiency in Florida (see the later section on zinc deficiency). This results in some modification of the growth symptoms owing to the growth-restraining characteristics of zinc deficiency. There is also considerable evidence to indicate that copper deficiency restrains absorption of zinc by the roots, so that in acute cases of copper deficiency symptoms of zinc deficiency almost always develop even though the amount of available zinc in the soil is adequate for healthy trees.

Copper deficiency frequently occurs on acid sands, associated with magnesium deficiency, without the exaggerated growth symptoms characteristic of copper deficiency, although very short dead twigs occur which are a miniature reproduction of the uncomplicated symptoms. While in California it is not uncommon to find copper and zinc deficiencies occurring together, copper deficiency is very frequently seen without the zinc complication. See figure 6 and



Courtesy of California Agricultural Experiment Station

Figure 6.—Copper deficiency: Left, sucker growth showing gum blisters and gum pockets; center, young lemon fruit showing gum pockets around central pith, and rough exterior; right, mature orange fruit showing gum excrescence on rind and splitting tendency; mature orange showing scabby, reddish-brown, cracked appearance of rind, gum pockets around central pith, and semi-gelatinized juice vesicles.

plates 4 and 5, pages 357, 358, for various pictures of fruit and twig symptoms of copper deficiency.

Cause and Treatment

Insufficient available copper in the soil is believed to be the primary cause of the symptoms described. In past years in Florida the symptoms were believed to have been due to too much nitrogen (then designated as ammonia in fertilizer mixtures), and this gave rise to the term "ammoniation." On the basis of available information the cause might be termed an unbalanced nitrogen-copper ratio,

but the term "copper deficiency" is preferred for the practical reason that copper applications constitute a specific remedy. The relation of copper deficiency to nitrogen utilization is not so evident in California as it is in Florida; recently, however, a number of cases have come to the attention of California workers in which the copper symptoms of gumming and dieback occurred on trees apparently excessively supplied with nitrogen.

Early treatments consisted of withholding nitrogenous fertilizers and inserting crystals of copper sulfate under the bark. Treatments in Florida now consist of copper sprays or applications of copper sulfate to the soil. Both methods are in common use. In California sprays appear to be the only satisfactory treatment. Recovery is extremely rapid, applications of the proper kind before growth starts in the spring resulting in a good setting of normal fruit on severely affected trees.

IRON DEFICIENCY

Iron deficiency has been recognized in California for many years, Lipman and Gordon (50) in 1925 and Thomas and Haas (78) in 1928 having reported on experiments for its control; and it is still a considerable problem under certain soil conditions. It has also been of importance on calcareous soils in Arizona, and Finch, Albert and Kinnison (28, 29) have reported on experiments to control it in the case of both citrus and eucalyptus. In Florida it occurs in an acute form in limited areas where the soil is closely underlain by limerock. Such soils are alkaline in reaction and subject to severe drought conditions, both of which may contribute to iron deficiency. Bahrt and Hughes (5) have reported on responses from ferrous sulfate applications to trees on acid sands in Florida but so far commercial treatments for iron deficiency have been unsatisfactory.

In Florida, iron deficiency is commonly associated with zinc, manganese and magnesium deficiencies, and applications of all these elements frequently result in material improvement of the trees and crop.

Symptoms

In iron deficiency citrus leaves are unusually thin with a very fine network of green veins on a much lighter background (figures 7, 8 and plate 6, page 359). In acute cases in Florida the entire leaf will be yellowish, often almost orange-colored, this being particularly noticeable on leaves of orange trees. Leaves of iron-deficient

Figure 7.—Iron deficiency on orange leaves showing fine, green venation on young leaves and spotted response to iron spray on the older leaves.

Courtesy of California Agricultural Experiment Station

grapefruit trees are small and very fragile when young and show a brown impregnation when older. Leaves shed freely, but in many cases the lower parts of the tree have a fair amount of good foliage while the top may show only sparse foliage and defoliated twigs. No particular twig symptoms have been noted, but there is considerable dying of twigs, particularly in the tops of trees, the entire tree eventually becoming involved. No particular fruit symptoms have been noted, but severely affected trees bear very little fruit.

In California, the reddish or brownish coloration of leaves is not common on any species of citrus which has been observed. The disorder is characterized primarily by light-colored foliage, particularly on the terminal twigs. The younger leaves are usually light green with a network of darker green veins. In more severe cases the young and old leaves become very pale, even whitish, the color of the smaller veins fading out until only a very pale green midrib

remains. At this stage necrotic spots often appear in older leaves which tend to drop at the terminals of the branches. New growth is sparse, and the trees die back and become reduced in size. Acute leaf symptoms are most common on the south side of affected trees. In this extreme form of the deficiency the fruit is small, hard, coarse, light in color and somewhat misshapen, especially in lemons.

Courtesy of California Agricultural Experiment Station

Figure 8.—Iron deficiency symptoms on lemon leaves.

Cause and Treatment

Iron deficiency is usually associated with too much alkalinity in the soil, but there also appears to be a definite relationship to extreme fluctuations in moisture supply. In California, many orchards affected with iron chlorosis have been materially helped or completely cured by more careful control of irrigation. Iron chlorosis is usually more severe in winter and spring than in summer. There is considerable evidence to show that the severity of the symptoms is affected by soil temperature and moisture relationships. Nutritional factors other than alkalinity also affect iron chlorosis. Hence no one cause can be universally assigned as the determining factor in the appearance of the deficiency symptoms. Correctional treatments are generally unsatisfactory in both California and Florida, although some recent experimental work is promising. Sprays pro-

duce only a spotted greening of the leaves rather than an overall greening (figure 7). The injection under pressure of solutions of ferrous sulfate into the trunks of affected orange trees has produced good experimental results in California, but the method has not been adopted on a commercial scale (75) owing to the transient nature of recovery, wood killing, and cost. Applications of iron salts to alkaline soils on which citrus trees showed typical iron deficiency have failed to give uniformly satisfactory results.

Fortunately, iron deficiency is not so widespread as some of the other deficiencies and presents a less important commercial problem. The literature with regard to the effects of iron treatments is complicated by the fact that in some cases reported response to treatment has subsequently been found to be due to impurities in the iron salt used.

MAGNESIUM DEFICIENCY

Magnesium deficiency has been a major problem on practically all citrus soils in Florida for many years, and leaf patterns corresponding to the Florida symptoms have been seen in California orchards for many years and have been reported by Chapman and Kelley (23) and Haas (42). Magnesium deficiency is also fairly widespread in Australia (55) and has been observed in both Argentina and Brazil. The first report of favorable response to magnesium applications in the field was by Averna-Sacca in Brazil in 1912, but this report apparently led to no commercial application. Bahrt (3) reported favorable response to magnesium applications in Florida in 1934, and further reports of a similar nature were made by Tait (76) and by Bryan and DeBusk (7) in 1936. Since then magnesium has become an integral part of the fertilization program for citrus in Florida and more recent work is summarized by Camp (10).

Reed and Haas (67) in California described symptoms of magnesium deficiency from sand cultures, and further information was supplied by Chapman and Kelley (23) also working with cultures.

The symptoms described in detail by Camp and Fudge (12) for orange and grapefruit trees in Florida, which parallel generally those described by Reed and Haas for citrus grown in cultures, will be followed in the description of symptoms.

Symptoms

Symptoms of magnesium deficiency may occur on leaves at any season of the year but commonly develop in the late summer or fall

appear as a result of translocation of magnesium from the leaves to the developing fruit, although there may also be such translocation from older leaves to young developing leaves on the same shoot. The mobility of magnesium in the tree differentiates it from iron, zinc, manganese and copper. The symptoms due to deficiencies of these elements develop coincidentally with the new growth and not on older leaves which previously have been normal in appearance.

Varieties producing seedy fruit are more severely affected than varieties producing seedless fruit. In adjoining plots on the same treatment seedy grapefruit may be almost defoliated while Marsh seedless trees with an even heavier crop of fruit are only slightly yellow; a similar phenomenon is common in oranges, seedy varieties like the Pineapple being severely affected while Hamlins, which are seedless, show only very slight yellowing. The yellowing is also related to the extent of fruiting. Heavily fruited limbs develop extreme deficiency symptoms and may even become completely defoliated while adjoining limbs with little or no fruit show no symptoms whatever. Again, this characteristic is most pronounced with seedy varieties. It may be aggravated by the tendency of seedy varieties to set fruit more unevenly on the tree than do the seedless varieties. The relationships of seediness to magnesium nutrition have been discussed in some detail by both Bahrt (3) and Fudge (34).

Alternation in bearing is common in seedy varieties growing under magnesium-deficient conditions. This is the result of the fact that when the trees are bearing a heavy crop, the loss of wood in the summer and fall as a result of defoliation reduces the fruit-bearing wood for the following year. The tree then goes through a season of recovery during which the leaves are green and little or no fruit is produced. The following year the tree may produce a good crop of fruit on the twigs of the previous year and again defoliate and die back. This alternation is a function of individual trees; some may be bearing fruit and others without fruit in the same year unless the cycle is set up by freeze damage or drought. Alternation in condition and yield may even pertain to parts of the same tree, certain branches bearing in one year and the others in the alternate year. This mixture of green, healthy-looking trees and yellow trees is very striking; and the occurrence of occasional trees that have one or two branches with yellow leaves and the rest with green leaves, or vice versa, aids greatly in the diagnosis of the deficiency.

Magnesium deficiency results in a great reduction in total crop,

when the crop is maturing. The leaves on which the symptoms appear are usually mature and were normal in color up to that time. Irregular yellow blotches start along the midribs of the leaves that are close to fruit and eventually coalesce to form an irregular yellow bank on each side of the midrib (plate 8, page 360). This area enlarges until only the tip and the base of the leaf are green, with the

Courtesy of Florida Agricultural Experiment Station

Figure 9.— Grapefruit trees acutely deficient in magnesium showing extreme defoliation in the fall of the year, with fruit left unprotected because of lack of foliage.

base showing a more or less inverted V-shaped area pointed on the midrib. This fading from green to yellow does not follow a fixed pattern, apparently being influenced by other nutritional factors and light, and possibly other factors, but in acute deficiencies the leaves eventually become entirely yellow. As soon as any considerable portion of the leaf has become yellow it may shed if conditions become unfavorable as a result of cold weather, toxic sprays or other shocks to the tree (figure 9), but if conditions continue favorable the yellowed leaf may remain on the tree for a long time. The defoliated twigs are weak and subject to fungus infection and usually die by the following spring, necessitating a heavy pruning of trees that have borne a heavy crop.

Fudge (34) has shown that magnesium-deficiency symptoms

though on occasional years there may be very large crops which are usually followed by complete crop failures. In the years when there is a crop of commercial size, there is also a reduction in the size of individual fruits and the fruit is weak and likely to give trouble in transit. Sites (71) and others have also shown that the fruit from magnesium-deficient trees is low in soluble solids and total acid

Courtesy of Florida Agricultural Experiment Station

Figure 10.—This picture shows the effects of freeze in Florida on the trees in the foreground which were supplied with nitrogen, phosphorus and potash, but were deficient in magnesium, manganese, copper and zinc. In the background are normal, undamaged trees which were supplied with the deficient elements.

and also in vitamin C. In oranges there is a very marked paleness of color of both pulp and peel. Magnesium appears to have more influence on the development of a rich orange color in the peel and the pulp than any other element.

Magnesium deficiency like other deficiencies makes trees more susceptible to cold injury than normal trees (49). This applies primarily to trees bearing a crop at the time of the freeze since on the off-year the trees may not be actually in a deficient condition. This susceptibility to cold damage applies to both tree and fruit, although it has not been determined whether the damage to the

fruit is due to an actual susceptibility or whether it is due to the fact that as a result of defoliation the fruits are exposed to the sky and consequently are colder because of radiation losses than protected fruit. This difference in cold resistance is not an academic matter but something of great moment to growers; on numerous occasions magnesium-deficient trees have been observed to lose all leaves, twigs and fruit while adjoining trees on the same fertility program plus magnesium lost only a few leaves (figure 10).

Cause and Treatment

Magnesium deficiency in citrus in Florida is caused primarily by the low level of magnesium in the soil. The deficiency is particularly acute on the light sandy soils from which magnesium readily leaches. This leaching of added magnesium is particularly rapid as the acidity increases (low pH). Formerly most of the citrus soils of this type had a pH of 4.5 to 5.0, and generally the fertilizer used was both physiologically acid and practically devoid of magnesium. The present program on such soils includes the use of dolomite to bring the pH up somewhere in the range of 5.5 to 6.0, which at the same time also furnishes some magnesium. Soluble magnesium, usually as the sulfate, is also applied to furnish quickly available magnesium. Occasionally, magnesium oxide is used as a pH corrective and to furnish magnesium but has not been entirely satisfactory. On soils with a pH higher than 5.5, soluble magnesium only is recommended and sometimes must be used in large amounts on calcareous soils. The program as used is given by Camp (10), with historical and technical explanations.

Some adjustment of magnesium fertilizer practices must be made to compensate for the level of potassium available to the trees. Fudge (35) has shown that the usual antagonism of potassium and calcium to magnesium exists in the field in a pronounced way. This has complicated most of the interpretation of experimental results. In practice, it means that levels for magnesium fertilization can be determined only in relation to potassium levels. At high levels of potassium availability, magnesium must be increased. The same situation holds with reference to calcium, and to get results the amounts of magnesium applied on calcareous soils must be greater than those applied on soils which are low in calcium.

In Florida, sprays have not proven effective in correcting magnesium deficiency—probably because the amount of magnesium needed is greater than that which can be absorbed by the leaves.

In California, magnesium sulfate has been tried by various workers on citrus trees showing the typical magnesium-deficiency patterns on individual leaves or twigs. In nearly all of the cases known to the authors no response has been noted. The common condition in Florida, in which the symptoms involve branches or whole trees which alternate their crops, has not been noted in California. The leaf symptoms referred to frequently occur on trees which are deficient in nitrogen, and in some instances these symptoms have persisted after very heavy applications of magnesium salts (Parker, unpublished). In other instances, they have been cleared up by the application of nitrogenous fertilizers or the elimination of deep cultivation. Recently, however, Haas (42) stated that magnesium sulfate applied just prior to an irrigation brought about a temporary response in citrus trees growing on a sandy soil near Tustin. A second case of response, where a combination of magnesium sulfate and urea was applied, has been reported by the same worker but in this instance magnesium sulfate alone gave no response. Inasmuch as California citrus soils are in general much better supplied with this element than Florida soils, and since irrigation waters also contain more or less dissolved magnesium, it appears that these symptoms under California conditions may be due in whole or in part to unbalanced conditions in the soil or the plant. In the light of the Florida experience, it also seems probable that excessive potassium aggravates this trouble. It is reasonable to believe that this factor, and possibly excess phosphorus, may be involved inasmuch as soil studies in California citrus orchards (15, 16) have revealed marked accumulations of both of these elements in the older citrus orchards. These accumulations are the result of the past use of manures and fertilizers containing these elements. Under California conditions nitrogen relations are sometimes a factor in the expression of the leaf symptoms described above.

MANGANESE DEFICIENCY

Manganese deficiency occurs commonly in Florida, responses to manganese applications having first been reported by Skinner and Bahrt (73) and by Skinner, Bahrt and Hughes (74). They were working with a complex of deficiencies, and it was not until 1938 that Camp and Peech (13) described the symptoms of manganese deficiency from the field and differentiated them from the other common deficiencies in Florida. More recently this deficiency has

been reported from California by Parker, Southwick and Chapman (64). It is now known to occur in many other citrus areas of the world. Delay in recognition of manganese-deficiency symptoms was due to their similarity to zinc-deficiency symptoms and to the fact that the symptoms of zinc deficiency override and mask them. Severe symptoms of iron deficiency also obscure the typical symptoms of manganese deficiency (62). The symptoms of manganese deficiency were described by Haas (37) from culture studies in California, but his descriptions do not correspond exactly with those given here, which are compiled from work done in the field in Florida and California. No common name is applied specifically to manganese deficiency, but in Florida a combination of zinc- and manganese-deficiency symptoms is known as "marl chlorosis" and acute symptoms on older leaves are sometimes classified as "bronzing," while in New Zealand, Taylor and Burns (77) refer to it as "mottle-leaf," a term commonly used for zinc-deficiency symptoms in most areas.

Symptoms

Young leaves show a fine network of green veins on a lighter green background, but the pattern is not so distinct as in zinc or iron deficiencies and the leaf is greener. As the leaf matures the pattern resolves itself, in the milder forms of manganese deficiency, into dark green, irregular bands along the midrib and main lateral veins with lighter green-colored areas between the veins (plate 9, page 361). With increasing severity several gradations in color occur (figure 11). Similar gradations for lemons are shown in plate 3, page 356, and figure 12. These range from light green to dull pale green splotches between the main lateral veins. Although the pattern approaches that of zinc deficiency it never develops the extreme contrast which characterizes the latter. If the deficiency is still more severe, the leaf assumes a dull-green or yellowish-green color along the midrib and main lateral veins, and the bands of these colors become more narrow while at the same time the interveinal areas become still more pale and dull. In extreme cases, in California, the interveinal leaf areas of oranges, lemons and grapefruit develop many whitish opaque spots which give the leaf a whitish or gray appearance. This whitish spotting has not been observed in Florida. Parker, Southwick and Chapman (64) have also observed that in California the leaf symptoms are generally most severe in the shaded portions of the trees. The leaves are not

Figure 11. — Manganese - deficiency symptoms on Valencia orange leaves. Top, mild deficiency, showing the lighter green color between the primary veins. One leaf has recovered its normal color as a result of painting with a dilute solution of a manganese salt. Bottom, severe deficiency symptoms. The young terminal leaves are light green in color with slightly darker midrib and lateral veins. In leaves of intermediate age the pale interveinal spaces embrace a larger area and the colors are dull. Older leaves at the base of the twig are extremely dull and light in color in areas between the veins, and many whitish spots have appeared.

Courtesy of California Agricultural Experiment Station

noticeably reduced in size or changed in form by manganese deficiency. Severely affected leaves acquire prematurely a senescent (aged) appearance and fall from the tree (63). Some limbs frequently lose more foliage than others with the result that the trees are unevenly foliated. When trees are only slightly affected the young leaves show a mild pattern which disappears after the flush of growth is completed. This is true in both Florida and California.

Parker, Chapman and Southwick (62) noted that, in the latter State, manganese deficiency appeared to be associated with a form of decline of lemon trees. However, treatment with manganese has not yet prevented the decline.

Symptoms of manganese deficiency similar to those which have

Figure 12.—Moderately severe symptoms of manganese deficiency on leaves of the Eureka lemon. (The color contrasts are generally greater in individual younger leaves and in mature leaves of lemons than in such leaves of oranges.) In old leaves the contrasts may be less marked in lemons.

Courtesy of California Agricultural Experiment Station

been described have also been developed in culture experiments by Chapman, Liebig and Parker (24). They noted the brown specks, distributed over the leaf, which had been described by Haas (37). A stippling of lighter colored spots in the light-green areas between the veins was also observed. However, these symptoms have not been consistently found in the field.

No particular twig symptoms have been reported, but in acute cases there is considerable loss of small wood. In Florida this is more noticeable in tangerines and Temple oranges than in other varieties. Dying of twigs is more noticeable in trees affected with

combinations of zinc and manganese deficiencies than in trees deficient only in manganese.

No striking fruit symptoms have been noted such as those characteristic of zinc and copper deficiencies. Skinner and Bahrt (73), Skinner, Bahrt and Hughes (74), and Bahrt and Hughes (4) have reported an intensification in skin color and juice color as well as increased firmness following applications of manganese to deficient trees, and Roy (69) has reported an increase in sugar in the juice. Later work in Florida shows the effect of manganese deficiency on fruit color to be much less pronounced than that of magnesium deficiency. In California the same effects of manganese deficiency have not been observed even in fruit from orchards which were very deficient in manganese, and the addition of this element resulted in no improvement of commercial grade or increase in size of the fruit (Parker, unpublished). The yields of citrus trees are apparently not reduced by mild forms of manganese deficiency in which the leaf symptoms appear and disappear from month to month. Reduction in yield does occur, however, when the leaves are more seriously affected and particularly when the foliage of the trees is reduced. Yield responses appear to depend upon increasing of the effective leaf area of the trees, as is the case in many other deficiencies.

Cause and Treatment

In Florida, manganese deficiency occurs on both acid and alkaline soils; it is probably due to leaching in the acid soils and to insolubility in the alkaline soils. On very acid sands it is commonly associated with deficiencies of zinc, copper and magnesium, as evidenced by both tree response and soil analysis. The most severe cases in California, however, have not necessarily been associated with marked zinc deficiency (63). Soil factors are not discussed in New Zealand reports. The artificial acidification of the naturally neutral or alkaline soils of California has been observed by Parker (unpublished) to decrease the severity of the deficiency symptoms, and culture studies by Chapman, Liebig and Parker (24) showed that manganese deficiency occurred in a neutral or alkaline medium (pH maintained at 7.0 or above) even though manganese was regularly supplied. Treatment by sprays of manganese sulfate neutralized with lime or lime-sulfur are used in Florida for deficient trees on alkaline soils, but on acid soils manganese sulfate is included in the fertilizer. Preliminary reports indicating corrective effects of sprays are also available from New Zealand. In Cali-

fornia, the treatment is by spraying. A single spray quickly clears up the pattern on younger leaves. Older leaves respond less rapidly and less completely. Several treatments may be needed before yield responses occur. Lemon leaves develop a toxicity pattern if sprayed too frequently or with sprays of too great concentration (63), but this effect has not been observed on other species of citrus.

NITROGEN DEFICIENCY

Identification of nitrogen-deficiency symptoms is somewhat involved because a peculiar type of leaf pattern, in which the tissue along the midrib and the larger veins is distinctly lighter in color than the remainder of the leaf, has been classified by Haas (in Fawcett (27)) as a symptom of nitrogen deficiency. His descriptions, however, would fit fairly well the pattern associated in the field primarily with girdling of the twig, limb or tree in such a way as to destroy or severely injure the food-conducting tissues without destroying the water-conducting tissues. When such girdling occurs the leaves become yellow along the midrib and larger veins, the remainder of the leaf usually remaining a dark dull-green color for a time and then fading slowly to yellow (plate 7, page 359). Tissues along the midrib and veins may become extremely light in color, giving rise to the terms "inverted frenching" and "vein chlorosis." The pattern can be produced artificially by girdling a twig or branch, but it is associated in the field in Florida with root rot and gum diseases due to species of *Diplodia* and *Phomopsis*, which destroy the bark or roots, and with lightning injury which has girdled the tree; in California rodent injury and injury due to a fluctuating water table are likewise common causes. The affected portion of the tree can be healed only by supplying the missing conducting tissue, as by bridge grafting or inarching.

Though leaves affected as described are likely to have an abnormal chemical composition and to show deficiencies of a number of elements, particularly magnesium, this pattern can hardly be considered a deficiency in the sense in which the term is here used. Applications of specific elements are not indicated for correction but rather for the supplying of a new conducting tissue where this is easily possible. A very similar pattern appears on older leaves in some groves following a heavy flush of new growth. The leaves become more deeply colored, however, and then shed.

Deficiency symptoms that respond to applications of nitrogen are almost too well known to need description, but since they may

be confused in some instances attention is called to some of the outstanding characteristics involved. Nitrogen-deficiency symptoms fall into two classes—symptoms on the trees that are continuously starved for nitrogen and symptoms brought on by a sharp decline in nitrogen supply. The second type of deficiency is not extremely common in Florida but does occur occasionally in an acute form when the nitrogen supply falls during the period of maximum fruit development. The following descriptions apply strictly to what may be accurately termed nitrogen-deficiency symptoms.

Symptoms

If nitrogen is deficient when growth begins, the young leaves are undersized, thin and fragile and develop a very light-green color (plate 10, page 362) which may ultimately become yellow if any fruit is produced. Shedding of leaves is heavy on such trees, and consequently the foliage is sparse. This type of symptom is common in unfertilized trees. The second type of pattern may develop when the trees have sufficient nitrogen during the spring, put on a heavy normal growth and bear a normal crop, and then become acutely deficient in nitrogen during the summer and fall when the fruit is maturing and there is a heavy drain on the trees. Under such conditions some of the green leaves slowly bleach to a mottled, irregular, green and yellow pattern and may ultimately become entirely yellow and shed. This pattern slightly resembles the symptoms of magnesium deficiency. The condition has been observed frequently in ridge groves that are not sufficiently fertilized in summer to take care of the crop of fruit. Trees growing on ridged soils are limited in root space, and this condition is further accentuated by the waterlogging of part of the ridge during the rainy season. Deep cultivation sometimes appears to cause the same effect in California.

Though no specific twig or growth symptoms have been identified, trees that are constantly short of nitrogen are stunted and unsymmetrical in shape and the growth is very short and irregular. The lack of foliage results in an open appearance. Considerable twig dieback occurs and the tree looks brushy (figure 13). Such trees seldom die but they remain in a permanently stunted condition unless nitrogen is supplied in adequate amounts. Orange and grapefruit trees deficient in nitrogen frequently produce fruit of a good quality as far as texture and flavor are concerned, but the crop is very small and the fruit is at times somewhat pale in color, the rind

is smooth, and fruit size is decreased. In California, lemon trees growing under conditions of deficient nitrogen show less change in color of leaves than do orange trees. There is, however, a great decrease in vigor and the trees mature their fruit prematurely before it reaches picking size. Jones, Van Horn and Finch (48) have reported on the effects of nitrogen levels on fruit quality under Arizona conditions but they have not specifically described deficiency symptoms.

Courtesy of California Agricultural Experiment Station

Figure 13.—Nitrogen-deficient Washington Navel orange tree (left) and comparable tree (right) which was supplied with nitrogen in the form of urea. Winter cover crops were grown in each case. In contrast with the fertilized tree, the deficient tree had sparse foliage of light green color, while some leaves were distinctly yellow. The new growth was very limited, and crop production had dropped to a very low level.

The ability to distinguish between true nitrogen deficiency and deficiency of other elements is important. This is particularly true in the case of magnesium deficiency. It must always be remembered that yellow leaves are not necessarily, or in fact commonly in Florida, an indication of nitrogen deficiency.

Cause and Treatment

While the cause of the first type of nitrogen deficiency is simply a lack of nitrogen in the soil, there is some evidence that the second may be produced in regions of heavy summer rainfall and very porous soil by a failure either to time the summer applications properly or to judge accurately the amount of nitrogen necessary to mature the crop. There is some indication that improper nitri-

fication due to waterlogging of the soil during the summer rainy season may result in a temporary deficiency of nitrogen which is relieved by dry weather.

In California temporary nitrogen starvation is sometimes the result of excessive applications of organic matter or excessive competition by cover crops. Parker and Batchelor (61) reported that such competition resulted in decreased crops when it occurred at critical seasons, but the leaf symptoms may exist only temporarily. Nitrogen starvation may occur also as a result of excessive leaching due to heavy applications of irrigation water. In pot cultures using soil, the second type of symptoms has been produced by overdoses of phosphate, and there are indications from other work and observations that high phosphate levels in the soil may increase the nitrogen requirement.

In ordinary cases of nitrogen deficiency the obvious treatment is to supply nitrogen in the required amounts. In the case of acute deficiency due to fruit production, consideration should be given to the form of nitrogen and method of application, particularly in relation to irrigation, where it is used. The use of nitrates usually would be indicated, owing to their immediate availability. The subject of nitrogen fertilization is too complex, however, for complete discussion here.

PHOSPHORUS DEFICIENCY

Early work on phosphorus was done in cultures, and symptoms of the deficiency on cuttings have been produced in sand and solution cultures by Haas (38) of California. Chapman and Brown (18) have described phosphorus-deficiency symptoms on citrus trees grown in 55-gallon drums in a calcareous soil of low phosphate availability. Neller and Forsee (54), and Forsee and Neller (30), have described the symptoms from the field in Florida. This work was done on a muck soil almost devoid of phosphorus and on trees that were kept free of other deficiencies. Only those symptoms which were corrected when phosphates were supplied are used in this discussion.

Symptoms

Young citrus trees deprived of phosphorus in cultures showed a reduced growth rate (figure 14), with the older leaves losing their deep green color and luster and becoming faded green to bronze. Some of these leaves later developed necrotic areas (figure 15)

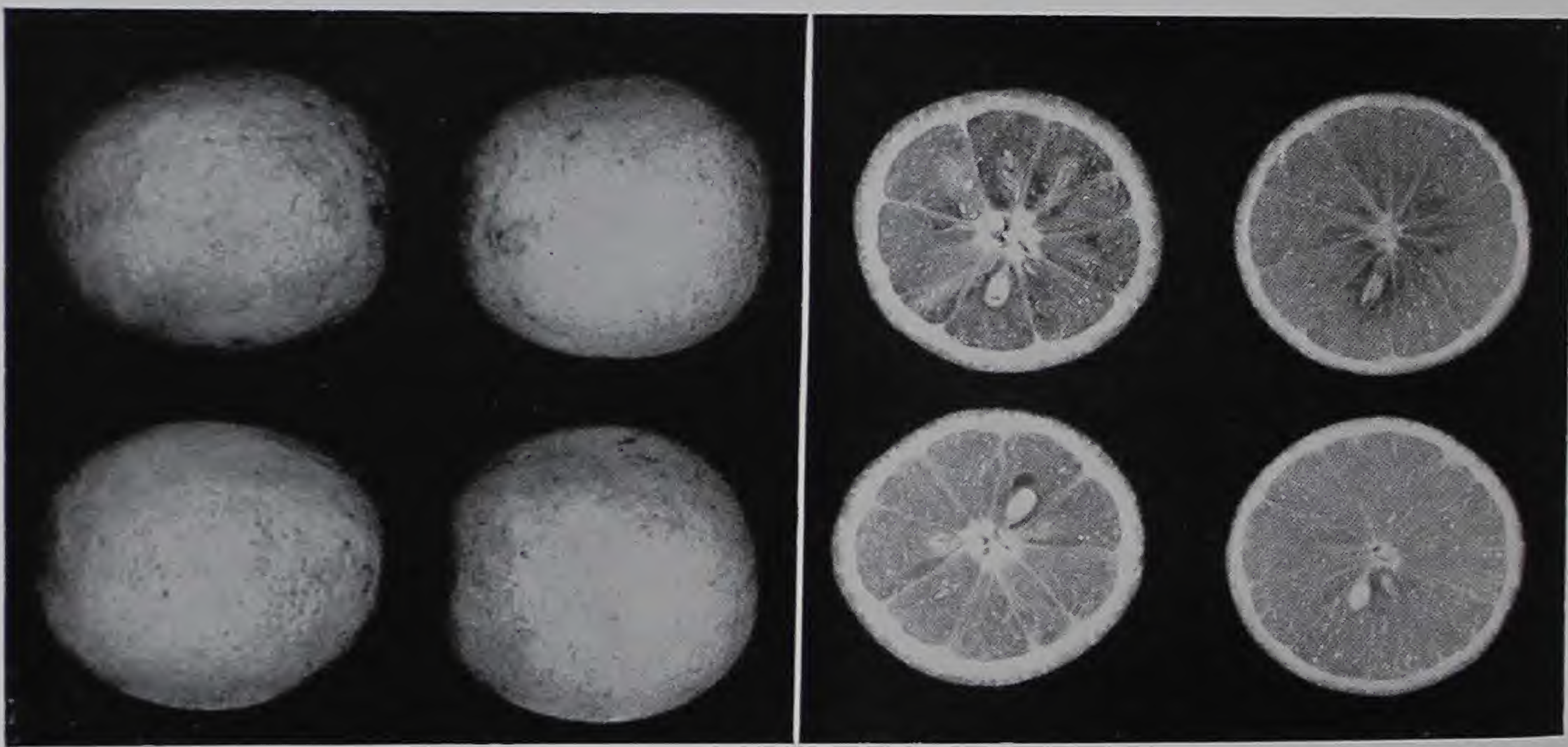
Courtesy of California Agricultural Experiment Station

Figure 14.—Phosphorus-deficient navel-orange tree (left) in comparison with tree of comparable age receiving phosphate (right). Note the restricted growth and fruiting on the phosphorus-deficient tree. These symptoms were produced in cultures.

Courtesy of California Agricultural Experiment Station

Figure 15.—Navel-orange leaves from phosphorus-deficient trees showing burned areas. This symptom does not occur on all leaves.

which had no definite pattern or position on the leaf. However, this burning was neither a general nor a consistent symptom; it was most prominent in the spring following bloom and a new cycle of growth. The affected leaves shed somewhat prematurely but the young growth continued, probably utilizing phosphorus translocated from older leaves, since the latter showed a reduced content and the young tissues a nearly normal content of both total and inorganic phosphorus. Young trees showed a sparse foliage owing to the re-



Courtesy of Florida Agricultural Experiment Station

Figure 16.—Lue Gim Gong oranges from trees deficient in phosphorus on the left and fruit from phosphorus-treated trees on the right in each picture.

stricted growth and shedding of leaves. Some twigs died back but this condition was not pronounced. There was a very limited flower development and no fruit was produced.

In the field in Florida phosphate-deficient trees were somewhat smaller with less vegetative growth. The leaves were narrower and smaller than normal and no burned areas on the leaves were noted. The fruit from deficient trees showed more pronounced symptoms than the trees, being coarse in texture with a thick, coarse skin (figure 16), and developed a premature softness. There was a heavy pre-harvest drop with up to two-thirds of the fruit dropping before normal harvesting time, and much of the remainder of the fruit was graded out because of softness, roughness or poor shape. The fruit from deficient trees was sour owing to high acidity in proportion to total soluble solids. These differences were consistent over several years and several samplings each year. The effect of phosphorus deficiency on the coarseness and acidity of the fruit has been

reported from several citrus regions (1, 2). Fruit effects similar to those described here were obtained by Chapman et al (18, 20, 21) in orange trees growing out of doors in large controlled water cultures.

Cause and Treatment

The cause of phosphorus deficiency is either a lack of phosphorus in the soil or a lack of available phosphorus. In the latter connection it should be noted that citrus appears to be able to obtain phosphorus more readily than many other plants, and conventional methods of determining available phosphorus are not tenable for citrus. Citrus grows freely in Brazil on soils which are so low in phosphorus that corn, cotton and many other crops will not grow properly without phosphate fertilization.

Corrective treatment is the use of phosphatic fertilizers, though difficulty is sometimes experienced in soils of high phosphorus-fixing power and where the rooting system of the tree is deep. Under such conditions it is sometimes necessary to induce a superficial root system by mulching.

POTASSIUM DEFICIENCY

The literature on the effects of potassium deficiency is somewhat bewildering and contradictory. This is brought about to a large extent by the fact that in many experiments the only problem that was being studied was the effect of potassium applications on a particular soil, without knowledge as to whether the trees involved were actually deficient or not, and also by the fact that in many experiments the existence of other deficiencies interfered with the interpretation of results. In the latter case the situation is complicated by the interaction of potassium, magnesium and calcium in the plant. In some of the early work in Florida increased magnesium deficiency was brought on by excessive potassium applications. In the case of publications describing fertilizer tests contrary reports largely arise from the fact that in some cases potassium was deficient and in others it was not deficient. A considerable body of knowledge has now accumulated from controlled culture studies, while the field knowledge is still somewhat fragmentary. Reed and Haas (65) in California and later Haas (40, 43) reported on symptoms produced on trees in culture. Chapman et al. of California, have carried out further extensive culture work (19, 20, 21, 22) under a wide range of cultural conditions, showing that although the symptoms vary somewhat with the variety, they are basically

constant throughout. This work included studies with 10-year-old navel and Valencia trees growing out of doors in large-sized solution cultures, and has provided a clear picture of growth foliage and fruit conditions associated with various stages of potassium deficiency. Eckstein, Bruno and Turrentine (26) reported leaf and fruit symptoms, but the conditions under which they were developed are not clear. In recent years there have been a number of reports on the effects of potassium applications in the field that indicated that the workers were actually dealing with deficient trees. These include Benton and Stokes (6), Bahrt (3), Anderssen (2), Allwright (1) and Roy (70). Sites (71, 72) has reported on the fruit symptoms of potassium deficiency as developed in the field in Florida. The last-mentioned work is of particular interest because all other deficiencies had been carefully eliminated in order that the study might be limited to potassium deficiency. The widespread use of potassium fertilizers and of organic materials such as manure, hay and straw on citrus has possibly prevented the common development of the symptoms even on light sandy soils.

Symptoms

The foliage and growth symptoms reported from solution, sand and soil cultures under controlled conditions involve first a slowing down of growth accompanied by an excessive shedding of leaves at blossom time. The new shoots are weak and often poorly attached to the twigs and the leaves are small. As the deficiency becomes more acute there is malformation of leaves and a fading of chlorophyll. The development of resinous impregnations has been reported, particularly with lemons and to some extent with other types of citrus, but these symptoms have not been observed under all conditions. Finally, in very acute deficiency there is a dying of twigs and a generally reduced size of the plant.

Symptoms as found in the field have not entirely paralleled the symptoms found in cultures but agree in general. In Florida carefully controlled field experiments in which all other deficiencies have been eliminated have given evidence of symptoms of insufficient potassium which are believed to be specific and not mixed with symptoms of other deficiencies. There was a slowing down in growth, particularly in the tops of old trees which had been subjected to a gradually increasing deficiency. The growth in these trees was weak and with a tendency for the young shoots to shed before they hardened. The leaves were small but gum lesions or

Figure 17.—Orange tree growing in water culture exhibiting acute potassium-deficiency symptoms. Note dieback, defoliation, malformation of leaves and general chlorotic condition.

Courtesy of California Agricultural Experiment Station

specific patterns have not been observed even though the trees have a very acute deficiency. The resinous lesions in the leaves reported by Bahrt have not been seen in recent experiments in Florida, but Haas (43, 44) reported such lesions in California, particularly in lemon groves, and showed a correlation with the potassium analysis of the leaves. Other workers have not corroborated these observations, however, and no records are available of correcting these symptoms by adding potassium fertilizers.

Other field symptoms which have been consistently observed in Florida are an increased susceptibility to cold and drought. Similar correlations are not reported for other areas.

Fruit symptoms of potassium deficiency, on which there is now general agreement by practically all workers, include a reduction in size of fruit and a very thin peel of smooth texture. There is also general agreement that a deficiency results in a tendency to premature shedding of fruit and a decrease in total acidity of the fruit and a consequent increase in the solids/acid ratio. Chapman et al. (*22*) showed that the fruit of potassium-deficient navel and Valencia trees had somewhat less acid, but that the total of solids was not affected. Sites (*72*) has shown in potassium-deficient grapefruit a definite reduction of soluble solids, total acid, and vitamin C in the juice. There have been a number of contradictory reports on the effect of potassium deficiency on the soluble solids and vitamin C content of the juice. These can perhaps be explained by the fact that some of the experiments were run under low levels of magnesium and as potassium was increased there developed a magnesium deficiency which reduced the solids content of the juice and thus leveled off the figures. Sites duplicated this condition in Florida experiments without going so far as to produce magnesium deficiency symptoms and found that solids could be reduced by an incipient magnesium deficiency which might go unnoticed. Illustrations depicting various tree, foliage and fruit symptoms of potassium deficiency as produced under controlled culture conditions on 10-year-old bearing orange trees growing out of doors (*22*) are shown in figures 17 and 18, and color pictures showing fruit characteristics associated with various levels of potassium under controlled conditions are shown in plate 11, page 363.

Cause and Treatment

In Florida proven evidence of potassium deficiency is available, the condition having been brought about in experiments in which only potassium is deficient. Correction has been achieved by the broadcast application of potassium chloride to the soil. No clear-cut evidence of responses to potassium fertilizer has as yet been definitely demonstrated in California. However, a large body of data has accumulated to show that broadcast applications of potassium fertilizers to most of the soils on which citrus is grown have resulted in increased absorption by the tree. For example, in the University of California Citrus Experiment Station plots, yearly broadcast

applications of one pound of potash in the form of potassium sulfate per tree have resulted in increased uptake of potassium by the tree, and is reflected in both the leaves and the fruit (unpublished data, Chapman, Jones, Parker and others). Heavier rates of application of potassium salts have resulted in greater increases in potassium content of the trees. Applications of manure to the soils have also resulted in increases of potassium in the soil and trees. Since

Courtesy of California Agricultural Experiment Station

Figure 18.—This picture shows fruit from potassium-deficient tree (left) compared with fruit of similar age from tree receiving ample potassium. Note reduced size and smooth rind of fruit lacking potassium; also reduced leaf size and malformation.

no definite growth or yield responses have been observed, the increased absorption of potassium by trees fertilized with potash fertilizers and manures may represent "luxury" consumption.

SULFUR DEFICIENCY

Sulfur deficiency has not been identified in the field, but a brief description of leaf symptoms on Valencia orange cuttings grown in sand cultures lacking sulfate has been given by Haas (39). Further information derived from both sand and soil cultures with young bearing orange trees and lemon, grapefruit and sweet-orange seedlings has been obtained by Chapman and Brown (17). The following brief description is from the latter work.

Courtesy of California Agricultural Experiment Station

Figure 19. — Effects of acute sulfur deficiency on oranges; shows weak, multiple and highly chlorotic shoots.

Symptoms

The leaf symptoms in general consisted of a chlorosis quite similar to that produced by nitrogen deficiency. Sulfur deficiency, however, was characterized at its onset by a much yellower new growth, the older leaves remaining green (plate 12, page 364). This contrast in coloration was marked and gave the trees a striking appearance. No abnormal twig characteristics developed, but some dying back occurred as the deficiency progressed (figure 19). The immature fruit from sulfur-deficient trees was a lighter green than normal fruit and the mature fruit was a lighter orange. Some of the fruits were dwarfed and misshapen and others had an abnormally thick peel. The interior of the fruit was pulpy and juiceless, with some of the juice sacs gelatinized as in granulation.

ZINC DEFICIENCY

Zinc deficiency is probably more widespread in citrus than any other except that of nitrogen, and its characteristic symptoms have been reported from practically every citrus-growing area. In California, investigations leading to the use of zinc as a corrective started about 1930, being conducted by Chandler, Hoagland and Hibbard (14) on little-leaf of deciduous trees and by Johnston (47) and by Parker (56, 57, 58, 60) on mottle-leaf of citrus. In Florida, the use of zinc on citrus trees was an outgrowth of work by Mowry and Camp (53) and by Camp (8) on zinc deficiency of tung trees and Satsuma oranges. As a result of work by Johnston in central California and by Parker and others in southern California, and by Camp, Reuther and Bahrt in Florida, zinc was in widespread commercial use in both States by 1934. Similarly favorable results have been reported from most of the other citrus-growing areas. The characteristic deficiency symptoms were produced and corrected in cultures by Chapman, Vanselow and Liebig (25). In Florida the symptoms are termed "frenching" and in California and many other areas "mottle-leaf."

Symptoms

The symptoms on mature leaves are striking. There are irregular green bands along the midrib and lateral veins, and the remaining tissue is light green, greenish yellow, or even a very pale yellow. The relative amounts of green and yellow tissue vary; in some leaves only the basal portion of the midrib is green, while others may show only splotches of yellow or pale green between the lateral veins.

Narrow leaves on twigs with short internodes are characteristic; in acute cases the leaves are very small with a tendency to stand erect (figures 20, 21, 22 and plate 13, page 365). Where the condition is mild the characteristic leaf pattern often starts on young leaves as a network of green veins on a light-green background. As the leaf matures the green veinal areas tend to broaden and deepen in color and the interveinal areas to become lighter (figure 22). Lemon leaves are not so distinctly mottled but are dull green in color, and they frequently have wavy margins. Mature green leaves have only occasionally been observed to develop the characteristic pattern. After treatment with a zinc spray, affected leaves become green, although they do not increase in size. The new leaves, however, are normal in both size and color (68) (figure 23).

Figure 20.—Valencia orange tree severely affected with zinc deficiency, showing dieback, small leaves and very small crop.

Courtesy of California Agricultural Experiment Station

When zinc deficiency is mild only a few terminal twigs may show the characteristic symptoms. In California these twigs are usually on the south side of the tree, but this has not been observed in Florida. When the deficiency is more acute, growth is usually slow, the entire outside of the tree bearing very fine, short twigs carrying the narrow, small leaves that have a tendency to stand upright (figure 24). These growth characteristics give the tree an upright, bushy appearance, and as time goes on the twigs die back over the outside of the tree, considerably reducing its size. As the outside of the tree dies back, water sprouts bearing nearly normal or slightly affected foliage develop on the main branches and trunk in the shaded portions of the trees. Thus, leaves showing great variation in intensity of symptoms are present on the tree at the same time. The very small twigs produce growth of normal appearance after zinc treatment, provided no other deficiencies are present. The increase in crop resulting from treatment is very marked (58, 59).

The fruits borne on the affected twigs vary in quality and number

Figure 21.—Valencia orange tree, showing response to treatment with sprays containing zinc. The condition of this tree was comparable to that of the tree shown in Figure 20 two years before this photograph was taken.

Courtesy of California Agricultural Experiment Station

in proportion to the severity of the zinc-deficiency symptoms exhibited by the respective twigs. Severely affected orange and grapefruit twigs in California are reported by Parker (59) as bearing small thick-skinned fruits (figure 25) whereas fruits from such twigs in Florida commonly have an unusually smooth light-colored, thin skin, but in both States the pulp is woody, dry and insipid. Parker also reports firm gum pockets occurring in the albedo of such fruits, but this has not been observed in Florida unless other deficiencies are present. Fruit on severely affected twigs of lemons in California is thin-skinned, juicy, elongated and pointed (figure 26). In lemons, acute zinc deficiency results in very small fruits of no commercial value.

The symptoms of zinc deficiency are so severe that they may mask or alter very markedly the symptoms of other deficiencies or disorders, and they often need to be corrected before an attempt is made to determine deficiencies of other elements.

Oranges exhibit the symptoms of zinc deficiency more often than do grapefruit or tangerines, although all types of citrus may be

Courtesy of California Agricultural Experiment Station

Figure 22.—Zinc-deficiency pattern on orange leaves.

Courtesy of Florida Agricultural Experiment Station

Figure 23.—Acute zinc-deficiency symptoms on Pineapple orange (left), showing very small, smooth fruit and pointed leaves with striking contrasts in the leaf pattern, and (right) fruit and foliage from a similar tree one year after treatment showing immediate resumption of normal growth.

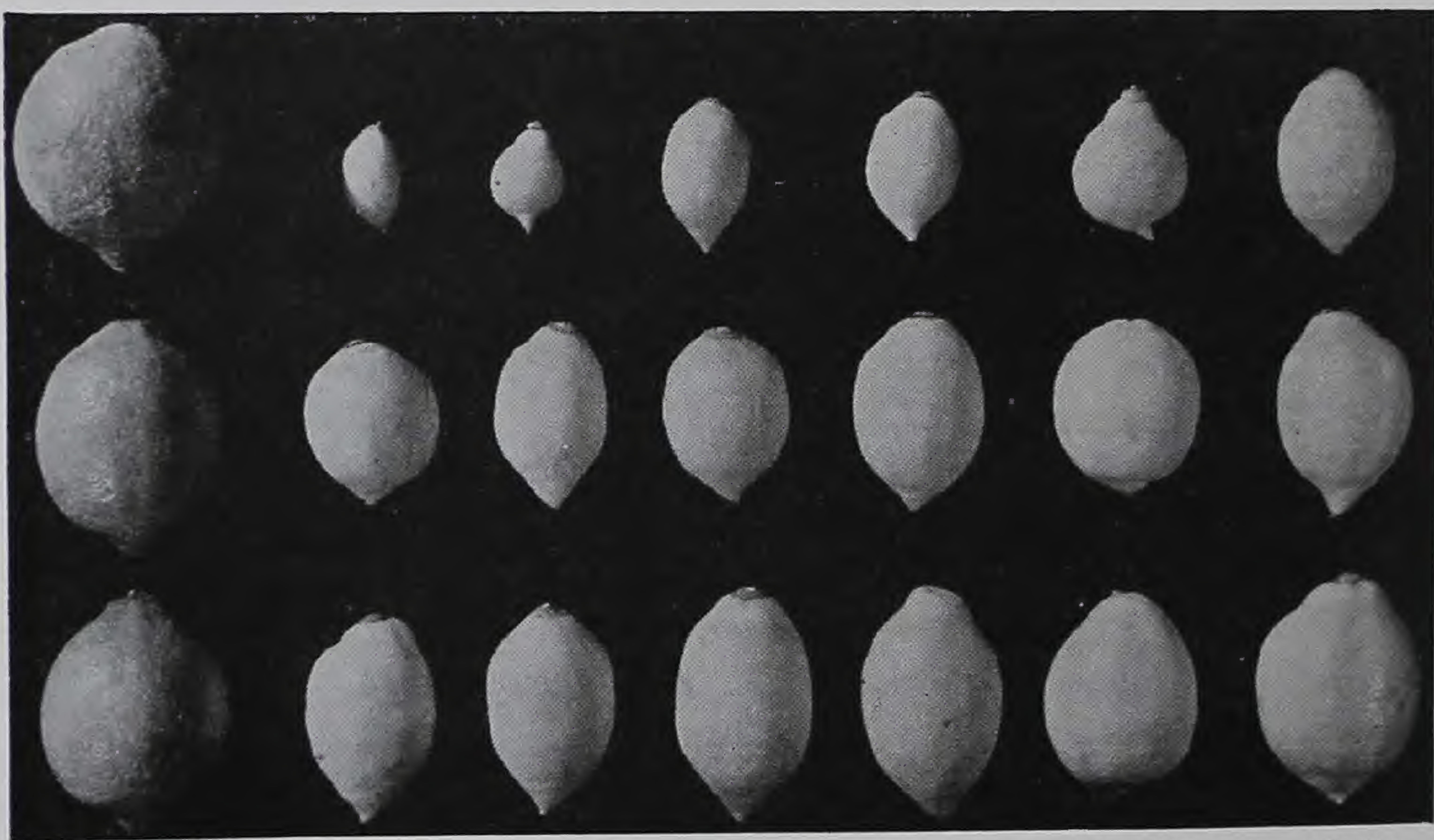
Courtesy of California Agricultural Experiment Station

Figure 24.—Acute symptoms of zinc deficiency in orange twigs showing small leaves, chlorosis and dying back

Courtesy of California Agricultural Experiment Station

Figure 25.—Grapefruit showing, on the left, the effects of acute zinc deficiency; center, fruit from similar tree two months after treatment showing discolored tough areas impregnated with gum in the thick rind; and, on the right, fruit from a similar tree treated 15 months previously.

affected. Deep tillage, lack of organic matter, or rootstocks unsuited to the soil may result in an increase of the symptoms. It appears that other factors which reduce the vigor of the tree have the same effect. Work in Florida apparently indicates that deficiencies of magnesium and copper reduce zinc intake through root injury, thereby giving rise to characteristic symptoms of zinc deficiency, even though the soil is not depleted of zinc. As a result



Courtesy of California Agricultural Experiment Station

Figure 26.—Normal lemons (left) in comparison with lemons from trees severely affected by zinc deficiency.

of the tendency of copper deficiency to intensify zinc deficiency, "frenching" (zinc deficiency) was frequently classed as a symptom of "dieback" (copper deficiency) by earlier workers. Because of this relationship, zinc-deficiency symptoms are very often reduced when a coincidental copper or magnesium deficiency is corrected—a response that is frequently misleading to casual observers. In such cases there is sufficient available zinc in the soil for the ordinary needs of the trees, but they are unable to absorb it until the requirements of the trees for copper or magnesium are supplied. When symptoms of zinc deficiency are brought on by a lack of available zinc in the soil, however, the trees respond only to zinc treatment. The various causes for zinc deficiency have been discussed in more detail by Camp (11). When deficiencies of other elements, such as nitrogen, cause a marked reduction of top growth

without seriously injuring the root system, the symptoms of zinc deficiency are usually mild. When nitrogen is supplied, however, an increase in growth occurs and on this new growth the zinc deficiency symptoms may be very severe (11).

Cause and Treatment

A deficiency of zinc in the soil commonly occurs in Florida, in California, and in other citrus areas where the soil has a low acidity (above pH 6.0) and is probably due to the formation of insoluble zinc compounds. In California the deficiency is not entirely dependent on soil reaction and is more prevalent on some soil types than on others. In Florida zinc deficiency also occurs on sandy soils of high acidity (pH 4.5 to 5.25); here it is probably due to the formation of acid-insoluble compounds (Jamison (46)). In Florida exhaustion by cropping (Camp (11)) also results apparently in zinc deficiency.

The treatment commonly recommended is the use of a spray of zinc sulfate neutralized with hydrated lime or lime-sulfur in Florida, while a spray of zinc sulfate with lime or soda ash or a zinc oxide spray is usually used in California. Soil treatments on alkaline soils have been unsatisfactory, but on some soils in Florida with a pH between 5.5 and 6.0 excellent response has been obtained from small applications of zinc sulfate (Mowry and Camp (53)). In the latter cases, the deficiency is believed to be due to exhaustion of the soil rather than to the formation of insoluble compounds.

KEY TO PLANT-NUTRIENT DEFICIENCY SYMPTOMS OF CITRUS FRUITS

	Element Deficient
A. Symptoms originating with new growth.	
B. Leaves uniform in color over entire area.	
C. Growth reduced, frequently resulting in bushy appearance.	
D. New leaves light green to yellow green, growth short	Nitrogen
D. New leaves very light yellow green to yellow, markedly yellower than above	Sulfur [2]
D. New leaves with water-soaked flecks becoming translucent, fruit with hard gummy lumps in the rind	Boron
D. Leaves green with fluting or tucking along midrib	Potassium
C. Growth greater than normal to excessive (not evident in California).	
D. Leaves usually large and very dark green, gummy excrescences on fruit and in axes of fruit segments	Copper
B. Leaves showing a pattern in which veins and midrib are darker than tissues between the veins.	
C. Leaves reduced in size, pointed, with sharply contrasting pattern of green along midrib and main laterals; tissue between the veins very pale green or yellow; fruit small	Zinc
C. Leaves approximately normal in shape and size.	
D. Dark green along midrib and main lateral veins with tissues between the veins lighter green to grayish; pattern not sharply defined and leaf dull color	Manganese
D. Fine network of green veins on very light green to yellow or whitish background, growth greatly reduced, and dying of twigs common	Iron
D. Fine network of green veins on light-green background with large leaves frequently malformed, fruit with gummy excrescences and gum in axes of segments	Copper
A. Symptoms originating on mature leaves and frequently associated with fruit production.	
B. Fading of chlorophyll starting in localized areas and gradually spreading.	
C. Fading of chlorophyll starting in blade of leaf parallel to midrib and spreading from there, but with base of leaf usually remaining green to very advanced stages	Magnesium
C. Fading of chlorophyll starting along edges of leaf and gradually involving areas between veins	Calcium [2]
B. Fading of chlorophyll not localized at start.	
C. Fading starting as mottled yellow green and yellow over entire leaf, which eventually becomes entirely yellow	Nitrogen
C. Fading of leaf to dull green and eventually to orange yellow; in extreme cases, burned areas on leaves	Phosphorus

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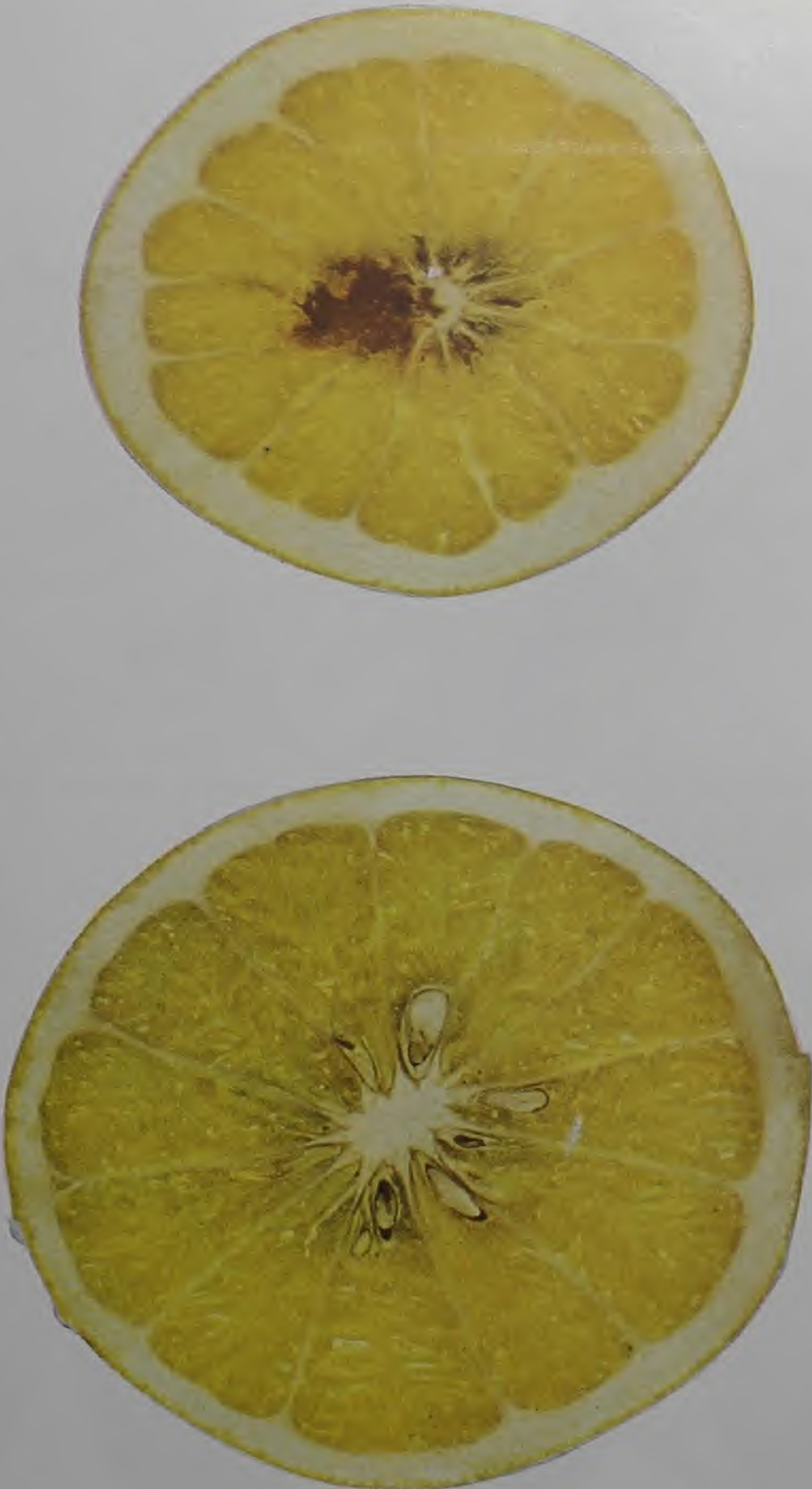


Courtesy of Florida Agricultural Experiment Station

Plate 1.—Grapefruit showing symptoms of boron deficiency as described by Morris in Rhodesia. Upper fruit shows aborted seed and gum pockets near the axis. Lower fruit shows part of the seed aborted without gum formation. The hard impregnations in the rind are not shown in either of these fruits.

Courtesy of California Agricultural Experiment Station

Plate 2.—Advanced stage of calcium deficiency on lemon leaves showing dead areas developed in the mesophyll regions.

Courtesy of California Agricultural Experiment Station

Plate 3.—Symptoms of manganese deficiency in lemon leaves. The leaf at the left shows very mild symptoms which become progressively more acute in leaves at the right. The symptoms shown by the leaf at the left are commonly seen in the field, but those on the other three leaves occur occasionally.

Courtesy of Florida Agricultural Experiment Station

Plate 4.—Copper deficiency in citrus, showing large leaves with weak twigs growing from multiple buds, which die back before they are fully developed.

Courtesy of Florida Agricultural Experiment Station

Plate 5.—Copper deficiency in Pineapple orange, showing brown excrescences on the surface of the fruit. Such fruits are also likely to have gum pockets in the rind and gum in the axes of the segments.

Courtesy of Florida Agricultural Experiment Station

Plate 6.—Iron deficiency in orange leaves, showing fine green veins on a yellow-green to yellow background and fine twig growth.

Courtesy of California Agricultural Experiment Station

Plate 7.—Leaves showing so-called vein chlorosis which is a result of girdling, rotting of the root, or any other injury that disrupts transfer of plant food.

Courtesy of Florida Agricultural Experiment Station

Plate 8.—Magnesium deficiency in grapefruit foliage showing yellowing of leaves adjacent to fruit. The yellowing starts near the midrib and gradually spreads outward until it takes in the entire leaf, after which the leaf sheds, frequently leaving the fruit on a long twig devoid of leaves.

Courtesy of Florida Agricultural Experiment Station

Plate 9.—Manganese deficiency on newly matured orange leaves, showing dark-green areas along the midrib and the main lateral veins and light-green areas between the veins. Note that the leaves are normal in size and shape. These leaves become very dull green at full maturity.

Courtesy of California Agricultural Experiment Station

Plate 10.—Orange leaves showing yellowing due to nitrogen deficiency.

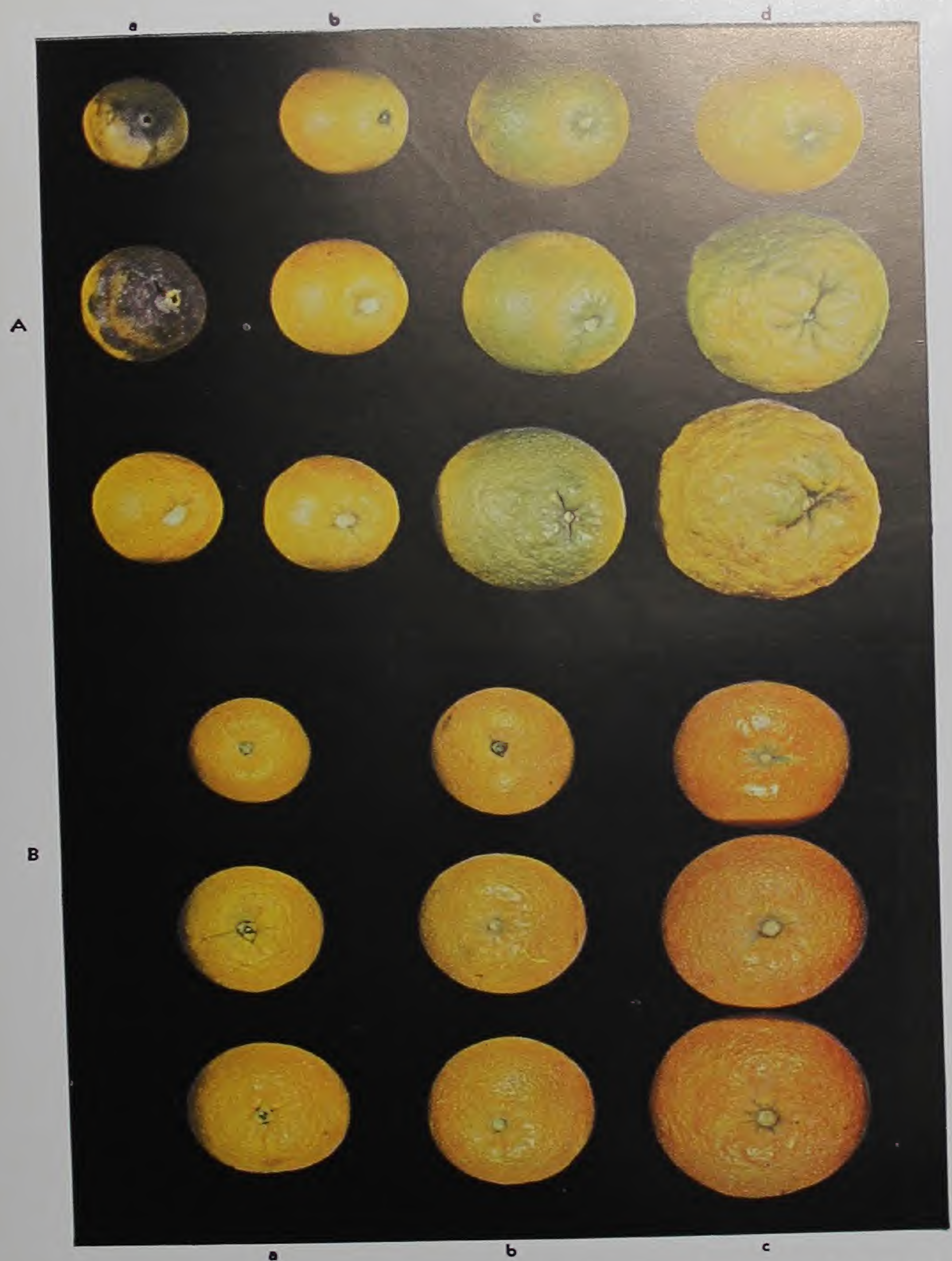


Plate 11.—Effects of varying potash supply on size and texture of oranges: A, Valencia oranges picked in October, 1943: a, fruit picked in October from trees suffering from acute potassium deficiency. The stems died back on some of these, leading to necrosis of the stem and of the fruit. b, fruit from tree only slightly deficient in potash. c, fruit from tree receiving ample potash. d, fruit from tree receiving excessive potash. B, navel oranges picked in 1944: a, fruit from acutely potash-deficient tree. b, fruit from tree slightly deficient in potash. c, fruit from tree receiving ample potash. (Reproduced from Hilgardia, Vol. 17, p. 650, by courtesy of the University of California Agricultural Experiment Station.)

Courtesy of California Agricultural Experiment Station

Plate 12.—Shoot from navel-orange tree in early stages of sulfur deficiency. New growth is very yellow as compared with older growth. Yellow leaves are similar in appearance to nitrogen-starved leaves. In a more acute stage of deficiency, the older leaves are less green than those shown here and many of them have a yellowish midrib. These symptoms are from trees grown in large containers of soil. Sulfur deficiency has not been identified in the field.

Courtesy of Florida Agricultural Experiment Station

Plate 13.—Zinc-deficiency symptoms showing dark-green coloration along the midrib and main lateral veins with tissue between the veins a light yellow. Note that the leaves are narrow and pointed and growth is very fine and upright in character. This gives the tree a bushy appearance.

APPENDIX

Indicator Plants

SOME species of plants are more sensitive to nutrient deficiencies than others, and even different varieties of the same crop may react differently on the same soil. For example, different inbred lines of corn all planted on the same day and in the same field may exhibit different degrees of hunger signs. Certain strains may appear normal, others may show slight signs of deficiency, while still others may exhibit severe hunger signs. Of course, deficiency symptoms will not appear if the soil contains an ample, balanced supply of plant food. On the other hand, if the quantity of plant nutrients furnished by the soil is not quite enough for full production, the more sensitive strains will exhibit hunger signs while the less sensitive ones may not show signs of hunger.

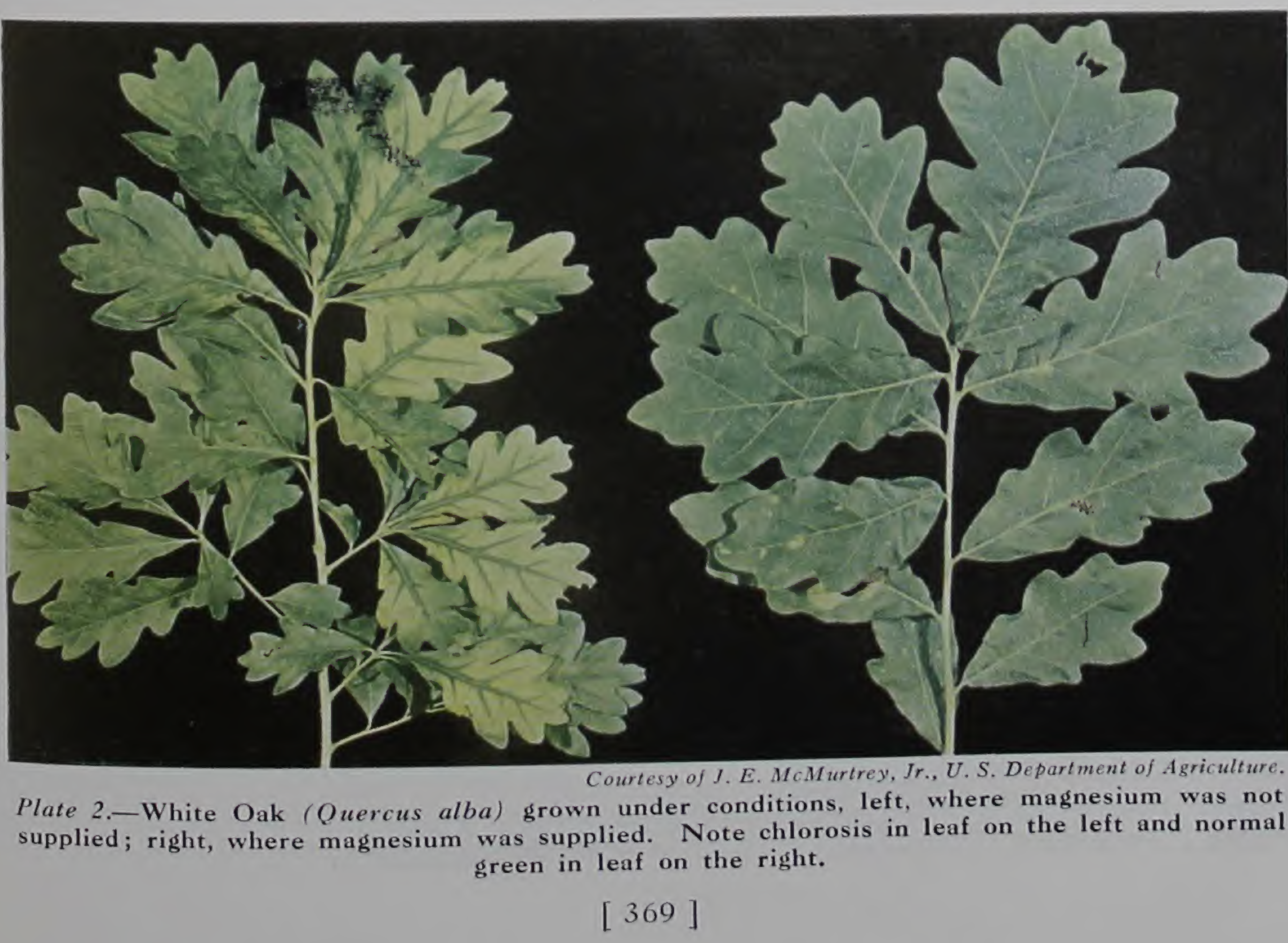
Agricultural scientists sometimes make use of deficiency symptoms in plants that are sensitive to a lack of nutrients to evaluate a soil's ability to yield up plant food. Such plants may be called "indicator plants." Different species or different crops may be used for checking on the status of the different plant nutrients in the soil. Unfortunately, hunger signs do not show up on most commercial varieties of crops until after the plant is somewhat starved and the yield may already be affected. Through the use of indicator plants the farmer can often determine whether commercial crops are threatened with starvation and, if need be, correct the situation.

Fortunately for man, many of our so-called pest plants—weeds, if you please—are excellent indicator plants and can be used for diagnosing the nutrient status of soils before actual deficiencies show up on the growing crops. Likewise, indicator plants are valuable as a guide with respect to the plant-food status of soils where the crops being grown are of types which do not develop characteristic hunger signs.

The colored plates on the following pages show deficiency symptoms in some of our common weeds. Many other weeds also are good indicator plants. Learn to recognize deficiency symptoms in weeds and in other natural vegetation, and you will have a valuable tool to aid in diagnosing hunger signs in crops.

Courtesy of American Potash Institute.

Plate 1.—Boron-deficient milkweed *(Asclepias syrica)*. Notice the upward curling of the leaves and the checked growth of the yellow terminal leaves and bud.

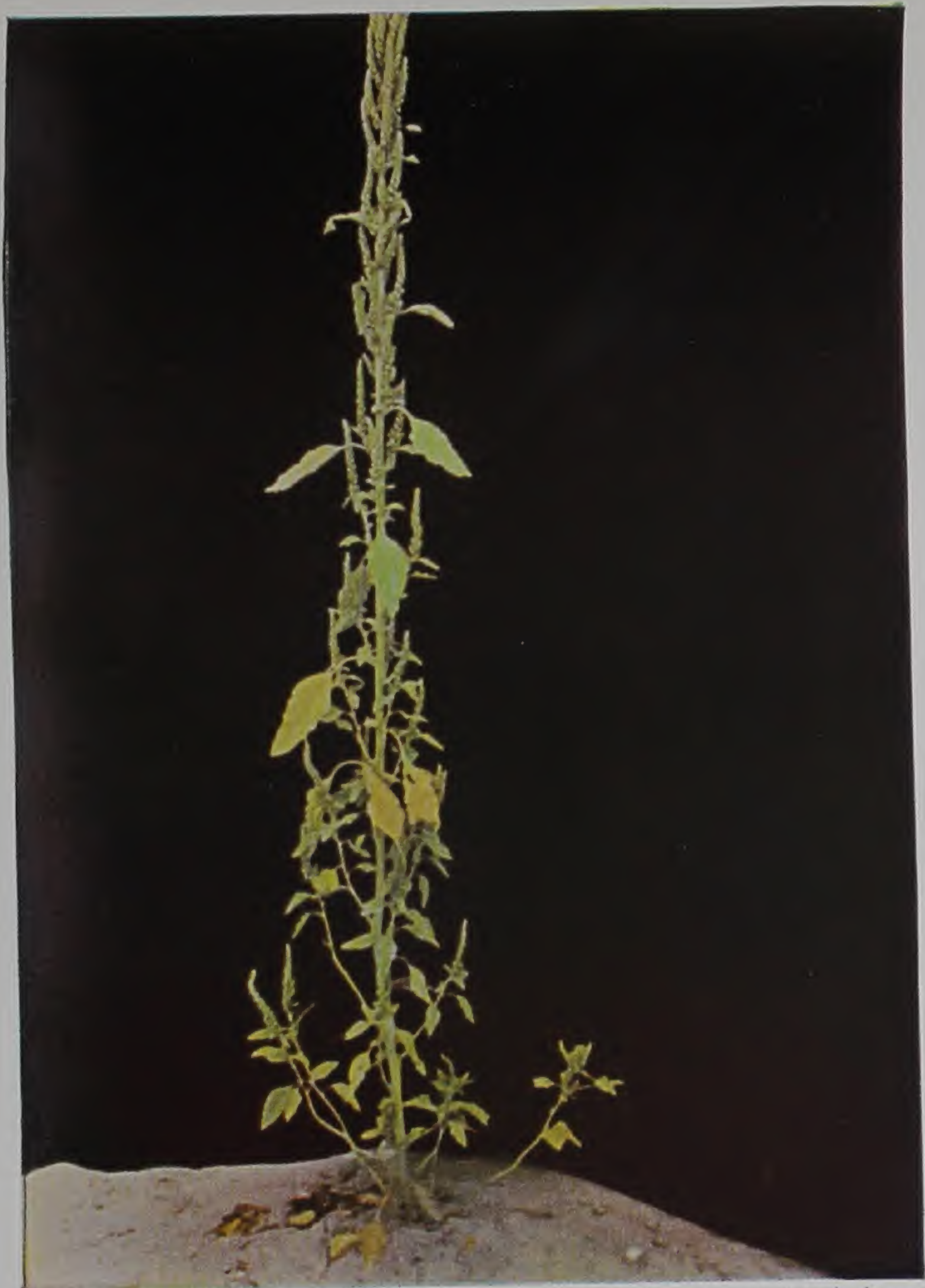


Courtesy of J. E. McMurtrey, Jr., U. S. Department of Agriculture.

Plate 2.—White Oak *(Quercus alba)* grown under conditions, left, where magnesium was not supplied; right, where magnesium was supplied. Note chlorosis in leaf on the left and normal green in leaf on the right.

Courtesy of J. E. McMurtrey, Jr., U. S. Department of Agriculture.
Plate 3.—Lamb's Quarters (*Chenopodium album*) grown under conditions of phosphorus shortage. Note reddening of older leaves.

Courtesy of J. E. McMurtrey, Jr., U. S. Department of Agriculture.
Plate 4.—Lamb's Quarters (*Chenopodium album*) grown under conditions of potassium shortage. Note chlorosis and necrosis of older leaves.



Courtesy of J. E. McMurtrey, Jr., U. S. Department of Agriculture.

Plate 5.—Pigweed *(Amaranthus hybridus)* grown under conditions of nitrogen shortage. Note light-green color of older leaves, lack of lateral branches and erect sparse growth.

Courtesy of American Potash Institute.

Plate 6.—Magnesium-deficient ground cherry *(Physalis sp.)*. Notice the distinct pattern of intervenal chlorosis. The lower leaves are the first to show the symptoms.

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